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GLACIAL AND INTERGLACIAL PERIODS IN EASTERN CANADA

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ABSTRACT

In a study of the Pleistocene of Newfoundland in this *Journal* (April-May, 1926) it was shown that the island had undergone two glaciations, a severe one in the early Pleistocene, separated by a long interglacial period from a late Pleistocene ice invasion of less intensity. As eastern Canada lies between Newfoundland, with its two glaciations, and the Toronto region, likewise showing two glaciations and an important interglacial period, it seemed very probable that it also must have been glaciated twice. Field work in Quebec and eastern Ontario has proved that this was the case, and it has been shown that deposits containing marine shells lie between two bowlder clays at a number of points between Gaspé and Brockville along the St. Lawrence and its tributaries. The interglacial time was long enough to permit profound weathering of the early glacial materials, so that comparatively little of the Kansan or Jerseyan till remains, accounting for the fact that the first glaciation has usually been overlooked.

There were more extensive changes of level in the interglacial time than in the postglacial history of the regions; but the two sets of marine beds have not been separated in previous studies of the Pleistocene of eastern Canada, thus causing much confusion.

The new point of view solves many difficulties in the interpretation of the drift deposits of the St. Lawrence and Gulf region, and harmonizes conflicting points of view.

INTRODUCTION

Three or perhaps four interglacial periods are recognized in the Mississippi Valley, and at least two have been found in the Cordilleran region, but only one has been worked out in Ontario, that of Toronto and Moose River; while east of this geologists have usually assumed that the ice age was unbroken by a mild interval. It is true that Sir William Dawson many years ago suggested a

slackening of the cold. "The facts indicate that there was an earlier and a later period of glacial action and dispersion of bowlders; that between these, in the middle Pleistocene period, large portions of the Northern Hemisphere possessed a climate not much colder than that enjoyed at present."[1]

He believed that the glacial deposits were formed by floating ice instead of sheets of land ice, and modern writers, convinced that ice sheets did the work, have paid little attention to his conclusions, so that the suggestion of milder conditions in mid-Pleistocene time has been overlooked.

To the present writer it has seemed unlikely that the eastern part of the continent should have been glaciated only once, while the center and western parts were ice covered at least twice, and probably three or four times, with intervening times of mild climate; but until recently no satisfactory evidence of an interglacial period has been reported in eastern Ontario or Quebec.

During two summers' field work in Newfoundland (1924–25) undoubted proofs were found that the island had undergone two glaciations, one in the early Pleistocene (Kansan or Jerseyan), the other in the late Pleistocene (Wisconsin), separated by a long interglacial period. The early glaciation was much more extensive and severe than the later one, the Labrador ice sheet at that time covering the whole of Newfoundland except the southern part of the Long Range, while in the Wisconsin glaciation only half of the island was covered with local ice caps and valley glaciers.

If there were two glaciations in the Toronto and Moose River regions on the west of the Labrador area, and also two in Newfoundland to the east, it could hardly be doubted that the territory between these extremes must have been twice glaciated, also, and it seemed desirable in 1925, after leaving Newfoundland, to test the matter in the field.

In Newfoundland the late glaciation was unmistakable on the lower ground, where U-shaped valleys, ice-carved surfaces, and fresh bowlder clay with striated stones were frequently found; but the work of the older ice sheet, though much more extensive, was much more obscure, because of long-continued and profound weathering in the interglacial time. In a few protected spots in the valleys hard

[1] *The Canadian Ice Age*, 1893, pp. 291–92.

and ancient till was found, and in one place a bed containing marine shells occurred between two bowlder clays; but the chief proofs of ancient ice action were found on high ground where foreign bowlders remained as greatly weathered remnants of the old till sheet.[1]

To find similar conditions in Quebec a visit was made to Baie St. Paul, where the Laurentide hills reach their highest points; and in a few days it was evident that there, also, two glaciations had occurred with a long interval of milder climate between them. The evidence for this will be given later in some detail.

It was decided to do enough field work in the summer of 1926 to test this conclusion in other parts of Quebec and in eastern Ontario.

Returning from the Geological Congress in Spain to prepare for this work, by an interesting coincidence, a manuscript entitled "New Discovery," by the late Dr. J. W. Spencer, reached me from Professor Wallace, of Manitoba University. In this there were accounts of sections in Quebec showing interglacial marine beds at various places, one of them being Baie St. Paul, where I had found the same relations the previous summer. Priority should therefore be accorded to Dr. Spencer for the discovery of interglacial beds in the lower St. Lawrence region. It is to be hoped that this paper will shortly be published; but in the meantime reference will be made to his discoveries in the following account of last summer's field work.

PREVIOUS ACCOUNTS OF THE PLEISTOCENE OF EASTERN CANADA

The eastern part of Canada has been studied by geologists for many years, and a complete review of the published references to the Pleistocene of the region would demand much space. Mention will be made here of only the more important publications bearing on the subject.

The most valuable of all is Dawson's *Canadian Ice Age*, in which the marine deposits and their fossils are described, and which contains suggestions of an interglacial time, as already mentioned. It was published in 1893, and though entirely wrong in ascribing nearly all the glacial features to floating ice, it is still of great use as referring to interesting sections of the drift which are now inaccessible.

The Geology of Canada (1863) and the later reports of the Geo-

[1] "The Pleistocene of Newfoundland," *Jour. Geol.*, Vol. XXXIV, No. 3 (1926), pp. 193–223.

logical Survey include many references to the eastern glacial and marine deposits, the most important accounts being those of Chalmers.[1] He mentions many localities where Leda clay and Saxicava sand occur in Quebec and New Brunswick, and gives details of glacial features, suggesting that there were two invasions of ice from the Laurentian region, as shown by striae running in two directions. He was not able, however, to find interglacial beds in Quebec.

He believed that the Laurentian ice did not cross the St. Lawrence, the glaciation on the southeast side of the river and gulf being due to local glaciers radiating from névé fields on the Appalachian and Gaspé mountains. The higher peaks rose above the névé as nunataks, and show only bowlders resulting from weathering. Land ice never covered the Magdalen Islands, or the eastern half of Prince Edward Island, though bowlders transported by floating ice when the sea stood at a higher level may be found on them. The higher ground in New Brunswick was not glaciated.

For our present purpose the most interesting part of Chalmers' reports is his account of a drift section at St. John, New Brunswick, where he found the following succession of deposits from above downward:

1. Bowlder clay.
2. Stratified bowlder clay.
3. Bowlder clay from 6 to 10 feet thick, like No. 1, but with shells scattered through the mass.
4. Laminated red clay with shells and a few bowlders, 4 feet.
5. Concealed by landslides, but probably unstratified bowlder clay.

Above No. 1 Chalmers found Leda clay and Saxicava sand up to 220 or 230 feet above the sea.[2]

It is evident from this account that the shell-bearing beds of St. John were deposited before the last advance of the ice, and, therefore, are interglacial; while the marine clay and sand above the

[1] *Geol. Survey Can.*, Vol. VI (1894), Part M, "Surface Geology of Eastern New Brunswick, Western Nova Scotia, and Part of Prince Edward Island"; Vol. X (1897), "Surface Geology and Auriferous Deposits of Southeastern Quebec"; Vol. XVI (1904), pp. 250 A ff., "Surface Geology of Eastern Quebec."

[2] *Geol. Survey Can.*, 1894, p. 36 M.

bowlder clay are postglacial, though Chalmers does not call attention to these relations.

No other reference to interglacial deposits was found in his reports, and he takes it for granted that the marine beds of eastern Ontario and Quebec are postglacial.

Accounts of the marine deposits of Ontario have been given by Ami,[1] Johnston,[2] and the present writer,[3] among others, but all have gone on the assumption that the deposits were postglacial.

Farther east Goldthwait[4] and the present writer[5] have referred to the marine beds as postglacial in Gaspé and Nova Scotia, and neither of us recognized that there was a second glaciation, though two distinct types of glacial deposits were noted in Gaspé, blue till with Archaean bowlders which must have come from the north side of the St. Lawrence, at low levels; and scattered bowlders derived from the mountains of the interior of the peninsula at higher points, evidently transported by local glaciers. The relative ages of the two deposits were not discussed, but the first-mentioned is probably Wisconsin, and the other Kansan or Jerseyan.

The work of the botanist, Fernald, should be mentioned also, since the finding of many endemic plants at the higher levels indicated that the Wisconsin glaciation did not reach these points,[6] though an early glaciation did so. His work in Newfoundland and Gaspé strongly supports the idea of separate glacial advances, one near the beginning of the Pleistocene, the other at its end.

The following account of the glacial and interglacial beds of Quebec and eastern Ontario will be founded mainly on the results of field work during the past summer. It will be understood, of course,

[1] "Contributions to the Palaeontology of the Post-Pliocene, Ottawa," *Naturalist*, Vol. XI, pp. 22–26.

[2] *Geol. Survey Can., Mem. 101* (1917), pp. 16–34.

[3] "Marine and Fresh Water Beaches of Ontario," *Bull. Geol. Soc. Amer.*, Vol. XII (1901), pp. 129–46.

[4] "Physiography of Nova Scotia," *Geol. Survey Can. Mem. 149* (1924), and other papers.

[5] "Physiography and Glacial Geology of Gaspé Peninsula," *Geol. Survey Can. Mus. Bull. 34* (1922).

[6] "The Persistence of Plants in Unglaciated Areas of Boreal America," *Mem. of the Gray Herbarium of Harvard University*, Vol. II.

that comparatively few points could be studied in two months' time; but the points chosen are widely enough scattered to give a good idea of conditions over the whole area. No reference will be made to sections which gave negative results. The work will be taken up from east to west beginning with the points nearest to Gaspé, where it is now recognized that two periods of glaciation are recorded: one by old and greatly weathered deposits consisting mostly of scattered bowlders at higher levels, and the other by young and fresh bowlder clay rising only a little above the sea.

GLACIAL AND INTERGLACIAL FEATURES SOUTH OF THE ST. LAWRENCE

Rimouski.—Blue bowlder clay with Archaean stones, evidently derived from the other side of the St. Lawrence, is found near the seashore, but does not rise upon the higher ground, where the surface consists of upturned slates. There are bowlders of fresh granite on the marine terraces, rafted over from the Laurentian region by ice floes when the sea stood higher; but on the hills few foreign bowlders occur, and these are interpreted as remnants of a till sheet formed by an early ice invasion, the finer materials having been removed, leaving only the more durable stones resting on the bare slate.

Bic.—Some time was spent in the neighborhood of Bic, a little port a few miles southwest of Rimouski, because Dr. Fernald had found a large number of endemic plants on its cliffs and hills, suggesting that ice could not have covered the higher ground in the late Pleistocene.[1]

On the seashore at low tide one finds striae running south and southeast on surfaces of slate. On the road up to the village there are eighty feet of fresh bowlder clay. These glacial features are attributed to Wisconsin ice crossing the St. Lawrence. As at Rimouski, there are large Archaean bowlders on marine terraces up to about 400 feet; but hills reaching 600 feet or more show bare slate or quartzite with residual soils on their lower flanks, and very few bowlders.

[1] *Ibid.*, p. 252.

Five miles southwest of Bic marine shells were seen resting on blue till 290 feet above the sea; and at 430 feet, near the edge of a terrace, gravels of a kamelike character are exposed; but it is not certain that the shells are interglacial.

Trois Pistoles.—Although Trois Pistoles was not visited last summer, it should be mentioned, since Dawson has described sections here in which marine clay is almost certainly interglacial. He found along the river and the railway 120 feet or more of Leda clay with marine shells resting on twenty feet of typical bowlder clay. The Leda clay includes a few large Laurentian bowlders. "A short distance westward of Trois Pistoles it is seen to be overlaid by a bowlder deposit, in some places consisting of large loose bowlders, in others approaching to the character of true bowlder clay."[1] Above the bowlder bed come sand and gravel with shells; and Dawson states that the section includes "bowlder clay below, next Leda clay, and above this a second bowlder drift associated with Saxicava sand. . . . . This is the arrangement which prevails throughout this part of Canada."

Riviere du Loup.—Sir William studied the drift near Cacouna and Riviere du Loup, also, and reports great numbers of Pleistocene shells, more than eighty species having been collected there. In this case, as at other points, he considers the whole succession of beds, including the bowlder clay, to have been deposited by floating ice, and speaks of "indubitable evidence of a marine bowlder clay, and this underlies the representative of the Leda clay and rests immediately on striated rock surfaces, the striae running northeast and southwest."

In my own work the river was followed inland, showing 190 feet of soft bowlder clay, probably of Wisconsin age, succeeded by bed rock of steeply tilted slate, sometimes bare and sometimes covered with a thin residual soil. A few bowlders of Archaean rocks rest upon it. Near the C.N.R. station, which is on a plain at 315 feet, cuttings for the railway disclose a few feet of very ancient sandy till crowded with bowlders and small stones and absolutely unlike the lower bowlder clay. The matrix is weathered brown and many of the bowlders are falling to pieces, though quartzites and

[1] *The Canadian Ice Age*, pp. 186–89.

some granites have resisted better. Limestone pebbles in masses of conglomerate have been completely weathered out.

The granites, gneisses, and greenstones of this till have evidently been transported from the Archaean region across the river, but so long ago that many of them have crumbled to pieces.

The Temiscouata railway runs inland from Riviere du Loup, and a visit was made to St. Honoré, 27 miles to the southeast, the highest point on the line (1,302 feet). Kamelike deposits were seen on the way up and also near St. Honoré station, some of the latter having been opened up as gravel pits. Most of the pebbles and bowlders are of local materials, though granites and gneisses occur. Weathering extends for several feet below the surface, giving a brown coloration. In this respect the fluvio-glacial deposits resemble the weathered till near Riviere du Loup station.

Rolling hills rise to 1,470 feet, and where fields have been cleared there are scattered bowlders of granite and greenstone, showing that ice from the Labrador center passed over them in the early Pleistocene glaciation. The contrast between the brown and deeply decayed ancient materials and the fresh blue clay with its well-preserved striated stones near sea-level is very striking and indicates a long time of weathering after the earlier deposits were laid down before the later ice advanced.

Several localities were examined to the southwest of those just mentioned, but the results were not decisive in most cases, and only one, in the eastern townships, will be mentioned.

Mount Orford.—This is the highest point in southern Quebec and is not far from the White Mountains in Vermont. Marine beaches were not to be looked for in this region, since the lowest point, Lake Mephramagog, is at 687 feet, well above the shell-bearing beds.

Bowlder clay with some striated stones is found on the lower flanks of the mountain, and at 1,524 feet a striated surface occurs, the ice having come from the north. The summit (2,580 feet) is of serpentine and shows no evidence of glaciation except a few foreign stones, including a large bowlder of gneissoid rock. Small pools of water on the very top suggest differential weathering.

It is probable that ice from the Labrador center reached within 600 feet of the top in the Wisconsin glaciation, since bowlder clay

seems fairly fresh up to that level. In this respect conditions are very different from those found near Bic and Riviere du Loup, 250 miles to the northeast.

THE PLEISTOCENE OF THE SAGUENAY REGION

The Saguenay is about in the latitude of Bic, but is nearer the Labrador center and might be expected to display more complete sections of the Pleistocene. Marine deposits and other features of the drift were reported from the Saguenay in the *Geology of Canada* (1863), and also by Dawson in the *Canadian Ice Age*, the latter writer referring to the smoothing and striation of the rocks due to a great local glacier moving toward the St. Lawrence; but so far as my reading goes no suggestion has been made of interglacial deposits.

Chicoutimi.—Striated and *moutonnées* surfaces of gneiss show that an important glacier coming from the Lake St. John Valley passed seaward through the Saguenay fiord, as suggested by Dawson. In many places the rock is covered with great thicknesses of drift, however.

Near Riviere du Bassin an excavation for a foundation showed six or eight feet of stratified clay overlain by two feet of bowlder clay and four feet of kamelike gravel. No shells were seen, but deep-water Leda clay often contains few or none of the tiny shells.

Along the sides of the deep valley, road sections show in one place 162 feet of well-stratified sandy clay resting on bowlder clay. Above this there are stratified clays containing a few bowlders, probably ice rafted, up to 198 feet. Slide material covers the upper part of the section at this point, but a ravine a little to the east discloses till up to 207 feet. The upper bowlder clay is soft and probably of Wisconsin age; but at sea-level near by, hard brownish clay occurs beneath the stratified sandy clay. No shells were found in the interglacial beds.

About two miles east of Chicoutimi, at Riviere du Moulin, a section displays a few feet of very stony till followed by a coarse deposit of cobbles mixed with some clay. Resting upon it are 10 feet of stratified sand and 6 feet of sandy clay, covered by a few feet of bowlder clay. No shells were found and one cannot be entirely sure that the stratified beds in either section are marine.

St. Joseph d'Alma.—Twenty-eight miles up stream from Chicoutimi a new power plant has been constructed at Isle Maligne, a mile or two from the village, and an interesting section is exposed where the river has been turned from its bed. *Moutonnées* surfaces of gneiss occur at various places, sometimes covered by 30 or 40 feet of very hard and stony till, on which rest 10 feet of stratified clay, followed by 20 feet of stratified sand. The indurated bottom till is strikingly different from the Wisconsin till seen higher up in the valley, but the two tills were nowhere found in the same section.

A mile and a half from the power plant a sand and gravel pit, reaching the level of the plain 275 feet above the sea, contains great numbers of shells of saxicava and macoma, but the deposit is probably postglacial.

No interglacial beds were observed near Chambord or Roberval on Lake St. John, and it is evident that the deep valley of the Saguenay was much more favorable for the preservation of the old bowlder clay and the stratified clays and sands above it than the broad shallow depression of Lake St. John.

Murray Bay or Malbaie.—Dawson gives a list of many species of marine shells found here, and Spencer, in a posthumous paper, "New Discovery," states that marine clay with shells reaches a level of 515 feet in the valley, and that in a ravine near Fraser Falls such beds are covered with till.

Dawson showed that the glaciation so apparent at Murray Bay was caused by a large valley glacier coming from the interior. This was true of the Wisconsin period; but probably the more ancient glaciation was due to a continental ice sheet coming from the Labrador focus.

Baie St. Paul.—Still farther to the southwest is the valley of Baie St. Paul, studied by myself in 1925, and by Spencer at an earlier time. This region was chosen by the writer to test the theory of multiple glaciations in Quebec, because the highest known peaks of the Laurentide hills occur near the village, which would give an opportunity to use the methods employed successfully in Newfoundland.

Fresh bowlder clay, striated surfaces, and hummocky moraines proved that ice had moved seaward down the valley in the late

Pleistocene; but the climb of a mountain reaching 3,000 feet, a few miles west of the village, gave unsatisfactory results as regards the ancient glaciation.

In Newfoundland foreign bowlders scattered over the mountains gave the best evidence of early Pleistocene ice work. On this mountain, however, no foreign bowlders were found, only a few deeply weathered Archaean stones like the underlying bed rock. It occurred to me, however, that the country to the north was all Archaean, so that bowlders different from the Archaean bed rock could not be looked for, thus leaving the question of glaciation uncertain.

In places the decay of granite has given rise to angular débris of quartz and feldspar forming a coarse sand in the hollows and exactly resembling occurrences found some years before on apparently unglaciated tablelands and mountains in Labrador.[1]

More decisive evidence of two glaciations was found in cuttings where roads lead out of the valley. Near an old mill a mile northwest of Baie St. Paul stratified clay (Leda clay) overlying hard, blue bowlder clay is crowded with marine shells of several species. The section begins 80 feet above sea-level and ends with 2 or 3 feet of unstratified clay at 140 feet above the sea. Whether the uppermost clay, which contains a few small stones, should be considered till seems uncertain.

About 2 miles southwest of the village the motor road toward Quebec rises upon the tableland and gives a good section of the drift. At 70 feet above the sea one finds blue till with striated pebbles of limestone, which is the underlying rock. On or in the till are many shells, usually whole and sometimes in pairs, indicating that the shellfish lived on a sea bottom of till.

Road cuts above this point show blue or brown sandy clay inclosing bits of limestone and broken shells up to 430 feet. Resting on the clay with broken shells there are fifteen feet of kame materials consisting of tumultuously bedded sand and cobbles with some bowlders reaching 2 or 3 feet in diameter.

The natural interpretation of these sections is that there was an earlier glaciation followed by a rise of the sea much above its present level, when 60 feet of stratified clay were deposited on a

[1] *Geol. Survey Can. Mem. 124*, pp. 26 ff.

bottom where shellfish flourished. Much later a valley glacier came down from the north, plowing up the shell-bearing stratified clay, mixing it with stones, and crushing most of the shells. This phase ended with the dumping of bowldery kame deposits over the till charged with broken shells. The Leda clay is therefore interglacial.

The steep eastern wall of the valley shows beds of gravel charged with shells of saxicava, macoma, and two other species up to the height of 385 feet. Above this there are kame deposits of sand, gravel, cobbles, and bowlders, suggesting that Saxicava gravel had been buried under aqueo-glacial deposits, and confirming the evidence obtained in the two other sections.

The proofs of Wisconsin glaciation are confined to the valley and do not extend to the mountains which rise above it to the east and west, though they were probably ice covered in the early glaciation.

It is uncertain whether the Wisconsin ice reaching the St. Lawrence through the Saguenay, Murray Bay, and Baie St. Paul valleys formed independent glaciers or only tongues of the main ice sheet to the north; but one inclines to the view that there were separate glaciers in these valleys during the late Pleistocene refrigeration.

On the road to Quebec.—The motor road connecting Baie St. Paul with the city of Quebec crosses a tableland which reaches an elevation of 2,265 feet (aneroid). On the higher parts one finds a few feet of sandy till containing bowlders of Laurentian rock, some of the gneiss bowlders being greatly weathered. At one point where the road slopes toward the St. Lawrence, 2 or 3 miles northeast of St. Joachim and 1,026 feet above sea-level, the gneiss beneath the till is greatly weathered also, no fresh rock being exposed in an excavation opened for road metal.

It is probable that the lobe of the Wisconsin ice sheet which covered the Quebec region did not rise to this level, and that the till found on the tableland is of early Pleistocene age.

THE REGION OF QUEBEC AND MONTREAL

Quebec.—The Pleistocene of the country near the city of Quebec is referred to in the older Geological Survey reports as well as in

Dawson's *Canadian Ice Age*[1] with no suggestion of two glaciations; but Spencer's manuscript indicates an interglacial bed of sand with shells of saxicava and macoma as occurring at Beauport between two sheets of bowlder clay. He mentions also shell beds under bowlder clay at Chaudiere Falls on the other side of the St. Lawrence, a few miles above Levis. Spencer found interglacial beds on Jacques River near Ecureuils station, about 30 miles west of Quebec. His localities were not visited by the present writer, but should be put on record.

Les Gres.—Near the small stations of Les Gres and La Gabelle on the way to Shawinigan Falls sections of 200 feet of drift occur along the railway and river, including bowlder clay, many feet of stratified Leda clay, and probably an upper bowlder clay, though no clean-cut succession was exposed because of extensive slumping. A very few fragments of shells and some wormholes were found in the Leda clay.

A more detailed study of this section and of others at Grandmere and Shawinigan would probably give more definite information as to glacial and interglacial relations.

Montreal and vicinity.—The Pleistocene sections at Montreal have received much attention, particularly from Dawson, who gives detailed accounts of two of them and mentions a great number of marine fossils from the Leda clay and Saxicava sand. He summarizes the drift of the region but does not suggest interglacial features.[2]

Spencer found till overlying Saxicava sand in one place, and considers the shell-bearing beds interglacial.

A section of about twenty-five feet on De Courcelles Street, near the Westmount station of the Canadian Pacific Railway, shows, from above downward, 3 or 4 feet of bowlder clay, 5 feet of sand with bowlders, and about 2 feet of stratified sand and clay resting on a lower bowlder clay. No shells were found, so that the sand may not be marine.

Near Oka, a few miles from Montreal, a gravel pit opened for road metal shows at the working face 5 feet of sandy gravel weath-

[1] *Canadian Ice Age*, p. 195.

[2] *Ibid.*, pp. 196–202.

ered brown and containing broken shells, mostly of macoma. At the unused opposite side of the pit the gravel is covered with sandy till inclosing bowlders 3 or 4 feet in diameter. The sand with shells is probably interglacial, though the section is not very satisfactory.

INTERGLACIAL MARINE BEDS IN EASTERN ONTARIO

Spencer's manuscript mentions interglacial marine beds at a number of places in Ontario a little west of the Quebec boundary and not far north of the St. Lawrence River. Several gravel pits containing shells were visited by myself near Wales and Mille Roches last summer, part of them apparently postglacial, with no suggestion of bowlder clay above them, as at St. Regis and Winter's pit; but others seem to be undoubtedly interglacial.

Murphy's pit on Lot 4, Con. III, in Cornwall Township shows at the bottom 8 or 10 feet of coarse sand and gravel with many shells, mostly saxicavas, but including also some macomas and parts of balani. The shells are generally whole and sometimes in pairs.

Above this come 6 or 8 feet of stony till with no sharp boundary between the two materials. The matrix of the till contains many crushed shells, as well as plentiful bowlders up to 3 feet in diameter. The glacial bed is of a morainic type, and the ice must have scraped up part of the shell-bearing gravel, mixing it with the other material it was carrying.

The workable part of the Clary gravel pit, on the west side of Lot 28, Con. I, of Cornwall Township, half a mile southwest of Mille Roches, consists of about 5 feet of coarse, subangular gravel containing unbroken shells. There is an overburden of very bowldery moraine, sometimes 10 feet in thickness. Some of the bowlders have diameters of 5 or even 9 feet, and a few of them are typically striated. There are broken shells in the matrix as in the former pit; and the shelly gravel is at the foot of a low morainic hill under which it passes. When the thickness of the moraine becomes too great, a part of the pit is abandoned and a fresh start made at a point where it is thin.

Spencer states that there are also marine interglacial beds across the river near Ogdensburg in the state of New York.

Marine fossils occur as far west as Brockville and as far north as

Lake Coulonge on the Ottawa River. Near the city of Ottawa a bowlder deposit has been referred to as overlying marine beds, suggesting a possible interglacial relationship, but this view is not supported by most writers on the Pleistocene of the Ottawa region, and Dr. W. A. Johnston, a very capable geologist, says that "no marine deposits are known to be overlain by till."[1]

Many deposits of Leda clay and Saxicava sand have been described from the region between the upper St. Lawrence and the Ottawa by Johnston, Antevs, and myself, but no proof has been found that any of them are interglacial.

The evidence just given of well-marked marine beds of interglacial age not far to the east seems to demand a re-examination of the shell-bearing clays and sands between Brockville and Ottawa with this point in view.

The time available for field work last summer was short, and part of it was spent on exploratory work which brought no results. It can hardly be doubted that a longer and more detailed survey of the extensive region touched last summer at more or less accidental points would add greatly to the known localities of interglacial marine beds in eastern Canada; and probably the lower parts of the northeastern United States would give similar results.

It is evident that eastern Canada, Newfoundland, and parts of the northeastern states were depressed below sea-level at two different times during the Pleistocene, the greatest depression having been in the interglacial period, since the earlier ice sheet of the Labrador center was thicker and more extensive than that of the Wisconsin. In Newfoundland and southern Labrador interglacial marine terraces can still be recognized in spite of slumping and later glaciation and they prove to be much higher than the post-Wisconsin terraces.

The two sets of marine deposits have not been separated in Ontario and Quebec, giving rise to confusion in the working out of ancient sea-levels. In confirmation of this fact it may be recalled that the fossils found in some of the deposits include seven or eight extinct species. It is most improbable that so many extinctions should have taken place since the last marine invasion, which ended

[1] "Pleistocene and Recent Deposits in the Vicinity of Ottawa," *Geol. Survey Can. Mem. 101* (1917), p. 15.

only a few thousand years ago and which has not been followed by important changes of climate. The extinct forms must belong to the early marine stage, which ended probably hundreds of thousands of years ago.

CONCLUSIONS

The foregoing paper shows that interglacial marine beds are known in eastern Ontario, in the St. Lawrence Valley and its tributaries in Quebec, in New Brunswick, and in Newfoundland. To this must be added the interglacial marine beds, 300 feet above sea-level, found by Dr. Parks in the Moose River region near James Bay.[1]

It will be understood that this type of evidence of an interglacial period can be found only below the highest level of marine shells; but where these are lacking the presence of two tills, one old and greatly weathered, the other fresh and little modified, proves a long interglacial time. Dr. Fernald's demonstration that endemic species of plants occur in places where only the first glaciation took place, but not where both are found, strongly supports the geological evidence.

It seems fairly certain that the early glaciation of the Lower St. Lawrence and Gulf regions was the work of a great ice sheet radiating from the Labrador center, and that it was much more severe and widespread than that of the last refrigeration, which in peripheral regions gave rise only to local valley glaciers.

The correlation of the events demonstrated in the eastern Pleistocene with the standard succession worked out in the Mississippi Valley is not easy, from the lack of connecting links between the two regions. The last refrigeration may safely be referred to the Wisconsin; but the earlier one might be either Kansan or pre-Kansan. Since a very old glaciation has been found to the southeast of the St. Lawrence in New Jersey, the first visitation of ice was probably of the same age and may be called Jerseyan.

The eastern interglacial period probably corresponds to the Toronto Interglacial Formation, which, as shown by its flora, was warmer than the present, and which had a long and complicated

[1] *Ontario Bureau of Mines Bull.*, Vol. XIII, Part I, p. 168.

history, including important changes of level. The Toronto formation has been correlated with the Sangamon in the Mississippi region; but it seems to me to belong farther back in the series, probably in the Yarmouth stage.

It may be that the eastern region was not invaded by Illinoian ice, and that its interglacial period included the Yarmouth, the Illinoian, and the Sangamon times. This would account for the great amount of weathering and destruction of the Jerseyan drift before the later till was deposited.

Among the abstracts of papers offered at the annual meeting of the Geological Society of America is one entitled "Three Pleistocene Tills in Maine," by Sayles and Antevs, in which it is stated that the lowest till contains much weathered bowlders. This and a second till, separated from it by 10 feet of sand and silt, have been thrown into folds. The latest (Wisconsin) till rests unconformably upon the eroded edges of the folds. They suggest that the lower tills may be Illinoian.[1] It seems probable that the lowest till is older than Illinoian, in fact, Jerseyan, and that it is to be correlated with the lowest till described in this paper.

GENERAL CONSIDERATIONS

There has been much divergence of opinion among geologists as to the Pleistocene history of eastern North America, especially in the lands surrounding the Gulf of St. Lawrence, good observers holding quite opposite views as to whether certain parts were glaciated once or twice or not at all, and also as to the source, extent, and thickness of the ice sheets.

In regard to Newfoundland, for instance, some have believed that an ice sheet coming from the Labrador center swept over the island; and others, that a local ice cap did the work which is so apparent in many localities. Both ideas are largely right; since the early glaciation seems to have come from the mainland to the northeast, while the later one was due to local ice caps and valley glaciers.

In Nova Scotia, also, there have been differences of opinion, some thinking that ice from Gaspé and New Brunswick advanced over

[1] *Geol. Soc. Amer. Prelim. List of Tilles and Abstracts*, 1926, p. 27.

the peninsula; and others, that the glaciation was from local centers. It is probable that both things happened, but at different times.

The Magdalen Islands were long described by excellent geologists as unglaciated, because of the presence of residual soils and of rugged hilltops; but Goldthwait landed on one of them and in twenty minutes found till with striated stones. The islands were covered with ice during the early glacial period when the Labrador sheet filled the Gulf of St. Lawrence; but its effects were removed from all exposed parts by long-continued weathering, the ancient till being preserved only in a few sheltered depressions.

The finding by Dr. Fernald of plants like those of the Shickshocks in Gaspé and the Long Range in Newfoundland confirms this conclusion.

From the foregoing examples it is clear that certain divergent views in regard to the Pleistocene history of the St. Lawrence and Gulf regions are harmonized by the fact that there were two glaciations, an early one of great severity, and a later one of less intensity. There are still difficulties, however, in fitting the results obtained in eastern Canada with those of the New England states.

The New England geologists report ice-transported bowlders on the summit of Mount Katahdin in Maine (5,385 feet), and even on Mount Washington (6,290 feet); but the present writer[1] and also Dr. Alcock[2] have found no evidence of glaciation above 3,500 or 4,000 feet on the Shickshock Mountains in Gaspé. The Shickshocks are nearer the supposed radiant center of the Labrador ice than the much higher New England mountains. Would it be possible for an ice sheet to deposit erratics on Mount Washington and leave untouched the summits of the Gaspé Mountains, which do not go above 4,450 feet and which are nearer the supposed center of glaciation?

These conflicting accounts of Pleistocene events in neighboring mountain regions seem hard to reconcile. There are, however, two possible solutions of the difficulty. It might be assumed that the Shickshocks were covered by the early Labrador glacier but that

[1] Physiography and Glacial Geology of Gaspé Peninsula, *Geol. Survey Can. Bull. 34*, pp. 31–37.

[2] "Mount Albert Map Area," *Geol. Survey Can. Mem. 144*, pp. 23–25.

the evidence has been so far destroyed in the long succeeding time that it has been overlooked by Alcock and myself. Or it might be supposed that the early glacial center was not where Low had placed it, but farther west. There is reason to believe that the Keewatin and Labrador ice sheets were at one time confluent, which implies a combined center of dispersion in the southern part of James Bay. In that case the White Mountains would be nearer the center than Gaspé, and might be ice covered when the summits of the Shickshocks escaped glaciation.

The latter supposition seems to me preferable and has the additional advantage that it would account for the glacial features of the Adirondacks, which show signs of early glaciation in the form of pebbles and bowlders of foreign origin reaching almost or quite to their summits at 5,000 feet; though bowlder clay and moraines are confined to the valleys and the lower slopes, having been deposited by the thinner Wisconsin ice.

In conclusion, it should be said that some of the points brought forward in explanation of the complicated Pleistocene history of eastern Canada require further investigation, so that this paper should be considered rather as a report of progress than a completed study of a difficult subject.

A SYNTECTIC PORPHYRY AT PORCUPINE

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ABSTRACT

As an answer to the question "What would be the effect upon the wall rocks if a granodiorite magma rich in superheat, alkali, and silica were to be injected into highly foliated meta-andesite schists which are saturated with ground water, the injection taking place in the hypabyssal region?" it is suggested that the schists would be converted into syntectic magma similar to the invading magma.

The prevailing country rock in the Porcupine district of northern Ontario consists of chloritized and generally highly metamorphosed Keewatin volcanic rocks, in part tuffs, but chiefly andesitic, basaltic, and dacitic lavas. This volcanic series was folded, eroded, and buried beneath conglomerates and graywackes of the Temiskaming period,[1] which then became infolded with the volcanics during renewed deformation. Following these events Haileyburian peridotite was injected into the region, and then, in the Algoman period, granites and acidic porphyries. In the Matachewan period there followed dikes of diabase. During the Animikian period a thick series of conglomerates and graywackes of supposed glacial origin[2] accumulated upon the greatly eroded complex; and these were injected by Keewenawan diabase dikes and sills. It is not known whether the Silurian and Devonian limestones of James Bay ever extended this far south and were eroded away, but it is certain that the Quaternary glaciers deposited their blankets of drift here over a deeply eroded peneplain from which even the Animikian sediments had been removed, only the infolded Temiskaming remaining.

In the heart of the district a number of quartz-feldspar porphyry stocks of Algoman age have been injected into and near a pre-Haileyburian synclinorium[3] 4 or 5 miles long and $2\frac{1}{2}$ miles wide, extending

[1] Cyril W. Knight, *31st Ann. Rep. Ont. Dept. Mines*, Vol. XXXI, Part II (1922), p. 30.

[2] A. P. Coleman, "The Lower Huronian Ice Age," *Jour. Geol.*, Vol. XVI (1908), p. 149.

[3] A. G. Burrows, *Ont. Bur. Mines Ann. Rept.*, Vol. III, Part II (1924).

from a little north of Porcupine Lake to a little south of Pearl Lake. The chloritic Keewatin schists, or greenstones, are highly foliated, the strike and dip of the foliae approximately paralleling the axial plane of the synclinorium as if due to a continuation of the same compressive forces. The foliae are usually warped into corrugations or flutings with prismatic diameters of from 1 millimeter to 3 or 4 inches, all of them pitching eastward at about 55°. The porphyry stocks are of elongated horizontal section, the long axes and numerous apophyses generally conforming to the strike and dip of the schistosity of the country rock, while the pitch or downward extension conforms to that of the flutings of the greenstone foliae. The porphyry itself is foliated also in exact conformity to the foliation of the greenstone, a condition which would seem to indicate that the porphyry had ascended in such a condition and manner as faithfully to follow the existing rock structure and that it had then been similarly foliated and fluted by the same forces. This is borne out by the inclusion in the porphyry of slabs of greenstone elongated in the directions of foliation and fluting, but under the microscope showing an absence of any indication of drawing-out as by shearing or compression.

ÉCOLE PHENOMENA

A number of years ago the writer described[1] the occurrence of elongated lenticules of porphyry about the size and shape of small fish in groups in the greenstone adjacent to the stock margins. They were so suggestive of schools of fish that the phenomenon was described as "*école* injection," in specific contrast to the older "*lit-par-lit* injection," from which it appeared to differ only in form. A recent restudy with the help of the microscope, however, convinced the writer that the lenticules were not injected but were spontaneously generated *in situ* as syntectic magma resulting from the close proximity of an acid hydromagma rich in alkali and silica.

A good typical example of this is to be found on the Porcupine Crown property near the town of Timmins on the north margin of a porphyry stock, about 200 feet north of the old mill. Here the *école* merges into the inclusion-rich margin of the stock by the grad-

[1] "The Rocks of the Porcupine District," *Can. Min. Inst. Trans.*, Vol. XVIII (1916), p. 256.

ual coalescence of the lenticules and dwindling of the intervening greenstone masses. It extends 300 or 400 feet westward along the

FIG. 1.—View looking down upon glaciated outcrop of contact between the porphyry (light) and the chlorite schist (dark) at Locality No. 10 on Porcupine Crown property. Note the transition from the *écale* to inclusion-rich porphyry. Note the coincidence of old and new structures.

stock margin, merging into the porphyry on its south side and into the unaffected greenstone on the north. For convenience of descrip-

tion its east end will be designated "Locality No. 10," and its west end, "Locality No. 11."

At Locality No. 10 the lenticules of porphyry are exposed in horizontal cross-section on a flat, glacially smoothed outcrop. Here their elongation parallel to the foliation of the greenstone is not pronounced, but is, nevertheless, clear and consistent with average dimensions of about 3×2 inches. For about 10 or 20 feet back from the approximate contact they dwindle in size and diminish in number; but as they approach it they increase in both size and number until they finally coalesce into a network inclosing isolated slabs of greenstone. In a similar manner these greenstone slabs decrease in size and number until within 12 or 15 feet they are scarcely discernible. The mass of clear porphyry into which they merge at this point is not extensive, and on the south passes into an immense area of inclusion-rich porphyry which may possibly represent the top of the stock (Fig. 1).

At Locality No. 11 the porphyry lenticules within 15 feet of the approximate contact occasionally attain dimensions as great as 6× 14×24 inches; and over an undetermined area, perhaps 50 feet square, they attain a maximum dimension approximating 1 foot. From this size they range downward to maxima of less than 1 inch, and even to vague whitish areas of half-porphyry and to small groups of feldspar crystals or single individual feldspars a few millimeters across. In fact, in the greenstone areas intervening between the lenticules there is a goodly sprinkling of such isolated crystals of feldspar. Also it is a conspicuous feature of the occurrence that the lateral margins of the lenticules, although fairly sharp usually, are occasionally vague; and the ends blend into the greenstone; while at other points among the lenticules areas occur resembling them in size and shape but apparently consisting merely of a whitish alteration of the greenstone (Fig. 2).

North and westward from this immediate locality the lenticules diminish until no indication of the porphyry remains save scattered feldspar individuals and discolorations of the greenstone.

At the west end of the Porcupine district there are ten or twelve such localities, and at the east end there are several more, of which probably the best are found at the Dome and West Dome Lake

Mines. At each of these one aspect or another is well exemplified; but the two localities just described are so typical and so accessible that the others need not be separately detailed; and what follows may be considered as applying to the Porcupine Crown localities in particular as to the others in general.

The microscope reveals exceedingly interesting and significant relations; but the metamorphic alteration of all the rocks involved is so extreme that the microscopic investigation has but little advantage over a careful field study of the outcrops. Nevertheless its testimony must be considered.

FIG. 2.—*École* at Locality No. 11 on Porcupine Crown property, showing typical lenticules of porphyry in schist. Note the albite crystals in the porphyry lenticules and in the adjacent schist. Longest lenticule 10 inches in length.

A thin section taken from the interior of a stock and probably representing clear porphyry shows, through the cloud of metamorphic sericite, paragonite, chlorite, dolomite, and secondary quartz, phenocrysts of acid plagioclase and quartz, with an infrequent ferro-magnesian mineral not now recognizable. In this connection chemical analysis must be invoked to interpret the thin section. This[1] yields approximately: silica 69.64 per cent, alumina 14.86 per cent, ferric and ferrous oxides 3.65 per cent, lime 2.51 per cent, magnesia 0.67 per cent, potash 2.44 per cent, soda 2.50 per cent, carbon dioxide 2.24 per cent, water 1.43 per cent, and sulphur 0.15 per cent, thus indicating the former presence of orthoclase and a trifling percentage of ferro-magnesian mineral which may or may not have contained some of the sodium.

Corresponding to the porphyry, the fresh greenstone at a distance from the stocks is much altered by ancient metamorphism;

[1] *Ont. Bur. Mines Rept.*, Vol. III, Part II, p. 35.

but frequently thin sections may be obtained which show it to consist of andesitic and basaltic material chiefly, with now and then some dacitic and even rhyolitic lavas. These various rocks are usually fine grained as would be expected of ordinary flows; and coarse crystals of any sort are not found, even the dacitic lavas showing only rather small quartz phenocrysts.

Chemical analyses of a couple of the lavas are given in the publication cited above.[1]

Chemical analyses were not made of the porphyry from the lenticules, but the microscope shows its petrographic characteristics to be essentially the same as the stock porphyry.

In one locality a thin section was made across a small lenticule $\frac{1}{2}$ inch wide. It seemed to the unaided eye to be a case of clear porphyry in clear greenstone separated by a sharp contact, and for that reason promised to be interesting. The microscope showed the central porphyry area to be good typical porphyry. The groundmass was microcrystalline and homogeneous, while the phenocrysts consisted in the usual rounded and embayed quartz crystals slightly fractured and showing undulatory extinction, the usual oligoclase showing albite twinning with and without pericline twinning, and a little hornblende. It was an especially interesting feature of this slide that it contained in the porphyry area a partly developed feldspar on the same scale as the others consisting only of an angle bounded by a dome and side pinacoid from which the feldspar faded out in the direction of the *C* axis into a few parallel strings of particles seeming to represent the skeleton of a half-formed phenocryst. Adjoining the porphyry area was a zone in which the porphyry blended with the greenstone; and the porphyry groundmass was not, as usual, the forerunner of the porphyry, but instead there were numerous large feldspar individuals, scarcely discernible for the large number of inclusions which they contained of chlorite, and many small plagioclase laths belonging originally to the greenstone. The nature of this transition from the metabasalt to quartz-feldspar porphyry is such, under the microscope, as strongly to suggest the metasomatic replacement of the older rock by the younger.

[1] *Ibid.*, p. 20.

The general rule of transition is best exemplified by a group of thin sections from Locality No. 11 taken across small slender lenticules or on their extreme ends, and out in the greenstone just beyond the fully developed lenticules where the unaided eye sees only a discolored greenstone sprinkled with large feldspar individuals. The smaller or incipient lenticules may have a few large quartz or feldspar individuals on the scale of the usual porphyry phenocrysts, surrounded, as a rule, by the characteristic porphyry groundmass consisting of small grains of quartz and feldspar with the prevalent carbonates, and sometimes a little chlorite. This appears to merge with the greenstone either as a vague blending, or as small tongues of groundmass penetrating into the greenstone on a microscopic scale, or by the sporadic development in the greenstone of large feldspars full of inclusions, or quartz areas partly rounded and clear-cut and partly interknit with the greenstone by means of fingers and granules of secondary quartz.

To understand the nature of the apparent assimilation or conversion of greenstone inclusions at Locality No. 10, a large number of thin sections were made from inclusions and porphyry in a prominent outcrop several hundred feet south of this locality, where it was more easy to obtain illustrative specimens. Here were repeated in reverse order all of the *école* phenomena of transition. The more resistant inclusions, in their interiors, appeared as metabasalt or meta-andesite with here and there a large foreign-looking oligoclase individual out of scale with the primary plagioclase laths; but nearer their margins large quartz and oligoclase individuals or pseudophenocrysts became increasingly abundant and at their margins merged into porphyry. This often contained chlorite in the proximity of the contact, which consisted in a mere zone of transition. The inclusions, however, were differently affected. Some of them appeared to be more resistant than others, or to have yielded to the transforming influence in unique ways, being, in some cases, evenly converted, with the nearly uniform development throughout their mass of the usual pseudophenocrysts giving them the aspect of unusually coarse-grained porphyry. In other cases they were more or less completely filled with threads, tongues, and sporadic spots resembling the porphyry groundmass.

This variety of aspects of inclusions is not difficult to understand in the light of the phenomena already cited, since the evidence of both field and microscope points strongly to subtle influences of conversion, which penetrate the greenstone along its lines of weakness and work upon it in a manner determined by local chemical and physical conditions. These might be expected to vary considerably within short radii when it is realized that the greenstones were originally flows and tuffs of four or five primary kinds afterward meta-

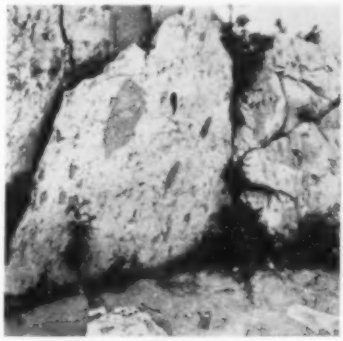

Fig. 3

Fig. 4

FIG. 3.—Inclusion-rich porphyry in old tailings pond of Porcupine Crown property. Note parallelism of schist inclusions.

FIG. 4.—Syntectic porphyry of the Schumacher stock near the Dome Mine, showing shadowy forms of transformed inclusions retaining the pitch of the preexisting schist flutings.

morphosed and deformed; and the lavas were characterized by flow and ellipsoidal structure.

In the light of these microscopic studies one may return to the field and feel greater assurance in the megascopic interpretation of the many phenomena observable in outcrops. He is able to realize, for instance, that his best guide is the delicate etching of glacially smoothed surfaces by the atmosphere and organic acids liberated by the decay of moss and other vegetation beneath the forest floor before the rocks were bared by man and fire. The intimately selective action of these agencies guided by slight differences in composition and texture has resulted in the revelation of most significant rela-

tions between the porphyry and its country rock. Thus are found examples in plenty of greenstone inclusions in porphyry which, after a certain amount of dwindling, blend into porphyry without discernible reaction rims. Notable outcrops are found which are composed almost wholly of such thickly massed inclusions, exhibiting all the characteristics of composition and texture which belong to the porphyry, the inclusions appearing as mere shadowy forms of vague outline. One such outcrop is exposed on the Schumacher property immediately north of the Dome Mine; and another stands up prominently on the Gold Center property (Figs. 3–5).

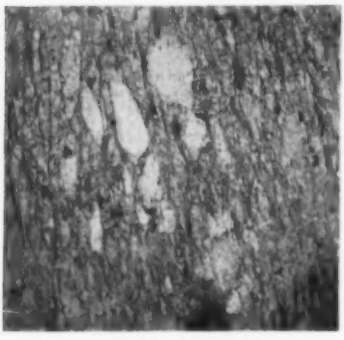

FIG. 5.—Syntectic porphyry of the Gold Center stock, showing relic forms of inclusions.

In all outcrops, as in all places where inclusions can be distinguished, every inclusion is angular and oriented parallel with every other and with the foliation and fluting of the adjacent greenstone, no case of rotation having been found.

In view of this important fact it is not surprising that on a broad flat outcrop on the southeast part of the West Dome Lake property near the highway, the porphyry in contact with Keewatin pillow lavas is found to possess the shadowy outlines of replaced pillows with here and there a small greenstone inclusion oriented in the usual manner to show that the sinuous outlines of former pillows are not flow lines of a viscous magma (Figs. 6 and 7).

Turning now to parts of the field beyond the *écoles*, abundant phenomena are found of no less significant a character. On the *école* margins, and just beyond them, the greenstone is affected by peculiar discoloration and fading in tonguelike extension of the *écoles*. Here and there this occurs in irregular patches; and at other points there are small spotted discolorations having the superficial aspect of a breccia. In two instances on the West Dome Lake property, one close to the spot just referred to and the other in the northeast corner

of the property, true pyroclastic breccias have been thus affected to the point of incipient and partial conversion. In these areas and others it appears that the vanguard processes consist first in car-

FIG. 6.—Ellipsoidal structure in Keewatin lava, representative of the greenstone invaded by the porphyry.

FIG. 7.—Relic ellipsoidal structure in the porphyry due to its replacement of the greenstone; West Dome Lake property.

FIG. 8.—Margin of *école* at Locality No. 8 east of Pearl Lake, showing tongue of syntectic influence extending into the schist with small patches of porphyry developed near its tip and surrounded by a border of incipient transition.

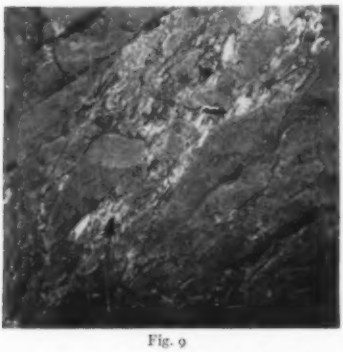

Fig. 9

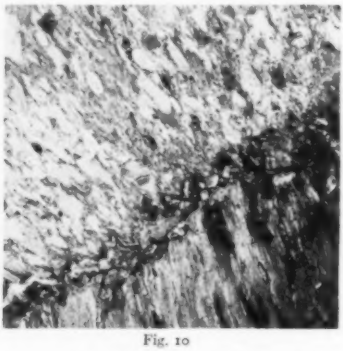

Fig. 10

FIG. 9.—Tongue of *école* breccia on east margin of West Dome Lake stock, showing the arrested transformation of Keewatin pyroclastic material into syntectic porphyry. Note the various degrees of transformation as indicated by the shades of gray.

FIG. 10.—Phenomenon similar to that of Fig. 9 in which the incipient alteration has been arrested at an old joint. Near the place of this photograph this intensification of the clastic structure broke through the barrier and made some progress beyond the joint.

bonation, then in silicification and carbonation, and then in the formation of sporadic feldspars (Figs. 8–10).

This carbonation consists in more or less perfect substitution of ferro-dolomite, usually accompanied by some sericite or paragonite, for the usual constituents of the normal greenstone, giving rise to a light-gray schist. This gray or "carbonate" schist occurs in large masses enveloping or accompanying the porphyry stocks, except in a few instances where it may reasonably be assumed to overlie stocks which have not reached the horizon of the present surface. One such case where mining operations have demonstrated the presence beneath the surface of a porphyry stock is on the old Rea property east of the town of Schumacher.

The whole group of *école* phenomena are characteristically marginal to the porphyry stocks; but a minor proportion of the true *écoles* have been found completely isolated from porphyry stocks, at least on the plane of the surface. However, in view of the close association of these cases with small areas of porphyry, which mining operations have proved to be tendril-like apophyses extending surfaceward from a deep stock, it is reasonable to suppose these to lie above the tips of still other apophyses. This is exemplified on the Goldale property at the east end of Pearl Lake.

Repeated efforts have been made, in breaking out lenticules and carefully examining numerous outcrops, to detect some sort of connection between the lenticules in support of the idea that by some unknown process they might have been injected along schist foliae in thin sheets, and have swelled here and there, somehow, at the expense of the adjacent rock. In fact, that idea was originally held by the writer, and so expressed in the initial description, in which this was referred to as a "marginal injection phenomenon." But no such connections could be found; and the writer was forced to the belief that they could not exist.

SYNTECTIC PORPHYRY

Any hope of being able to construe these elongated masses as due to drawing-out in a shearing process was immediately extinguished by the discovery that the quartz phenocrysts and pseudophenocrysts are not entirely crushed or even dislocated, and that the

feldspars are almost wholly unaffected by any sort of crushing or shearing. In this connection probably the most remarkable phenomenon in the whole galaxy is the sprinkling of large foreign feldspar individuals throughout the greenstone of the *école* areas and inclusions, for they certainly are of the porphyry, and are genetic associates of the porphyry lenticules.

The idea was originally entertained that the porphyry lenticules in some of their seemingly fragmental environment represented bowlders or perhaps bombs; but careful field work soon revealed the fact that the terrains in which they were found were not sheetlike formations, but irregular masses of much more compact form than conglomerate or agglomerate beds. Then it also became clear that they were characteristically located on stock margins and were marginal phenomena connected with the injection of the stocks, as indicated by the mere fact that they blended with the greenstone on one side and with the porphyry on the other.

This mergence of the *écoles* with inclusion-rich porphyry on the stock margins, in which the uniform orientation of inclusions indicates the stagnation of the magma at the time of development of the phenomena, seems to argue against the movement of porphyry through the greenstone to form the *écoles*. Furthermore, the lenticules have been proved to be isolated. This was a mere matter of labor with a sledge hammer. If the magma had been mobile enough to be squeezed along sheetlike passages too thin for microscopic detection, how could it have supported countless numbers of inclusions without permitting them to rise, sink, or rotate? On the other hand, if it were so viscous as to hold them thus, how could it have pervaded the greenstone as suggested.

If, by whatever means and in whatever condition, the magma had been injected, why should it have formed spindle-like swellings of the size, shape, and grouping of the lenticules? This idea of swelling calls for indications of expansion of the host rock under such a considerable addition of material; but not only are the schist foliae unwarped in the expected manner in the neighborhood of the *école* margins, but other structures are unaffected, such, for example, as the pillows of ellipsoidal basalt.

On the margins of the lenticules field and microscopic evidence

of replacement seems indisputable, and sharp contacts are rare, at least under the microscope. In line with this sort of evidence, the vague lenticule-like areas in the *écoles*, which are transitional between greenstone and porphyry, would seem, in the light of other microscopic evidence, already cited, to represent incipient replacement of greenstone by porphyry; and the sporadic quartz and feldspar pseudophenocrysts must represent another phase of the same process.

The porphyry with its hypabyssal texture might be expected to show marginal chilling, but instead of that the phenocrysts of the margins are often larger than those of the interior; and no clear case of marginal chilling has been found, not even among the lenticules. Instead of that, as the lenticules diminish in size, they frequently dwindle to a small knot of coarse feldspar individuals.

The dwindling of inclusions without rounding by fusion must be taken as indicating that their matrix rock was never a dry viscous magma, and that its action upon the inclusions was not that of physical fusion but rather of chemical dissolution; for in the case of a dry magma, the usual effect upon inclusions is to metamorphose them, to round them, and to enclose them in a reaction-rim. This perhaps is because the immobility of the medium makes an interchange of material between the inclusion and the matrix-fluid slow and imperfect, with the result that the principal influence affecting the inclusion is heat. On the other hand, when inclusions are sharp and angular, are merged with the host-rock by replacement, are transformed to similar material along lines of inherent weakness, and are not surrounded by reaction rims, it would seem that the attack upon them had not been by heat so much as by chemical influence, there being a mobile interchange of material between host-rock and guest-rock.

The transformation of the inclusions to porphyry in certain instances produces the illusion of inclusions of another coarser porphyry; but a careful study of a good outcrop will soon dispel this error because of the significant phenomenon of greenstone inclusions in all stages of transition into this porphyry. The transition is accomplished by the development of pseudophenocrysts in increasing numbers in the greenstone, followed by the conversion of their matrix

to a material resembling the porphyry groundmass, or else by the development of the groundmass first, and then the phenocrysts.

The form and character of typical *écoles*, and more particularly the peculiarities of the lenticules, incipient lenticules, and sporadic pseudophenocrysts, indicate that their origin could not have been by injection. As an invading magma the porphyry could have had no means of access to the space occupied by a lenticule nor any way of forcing its phenocrysts into the greenstone. The absence of chilled margins, even in the smallest masses most distant from the nearest stock, the gradual transition of one rock to another, and the *école* border zones of arrested transition, all co-operate to indicate that the *école* porphyry was not injected.

Whatever may be the ultimate answer to all the questions raised, the obvious aspect of the evidence is that it points to the conversion *in situ* of greenstone to porphyry, be the mechanism what it may.

MODUS OPERANDI

If lack of crushing and shearing among the phenocrysts of the lenticules can be accepted as excluding their origin by the squeezing apart of *lit-par-lit* bands, if the compact form of the *écoles* and their genetic association with the stocks, as indicated by their mergence into them, can be taken as refuting the idea of their clastic origin, and if the isolation of each lenticule from every other and the blending of the lenticules into greenstone by the two methods stated can be regarded as incompatible with any conceivable method of injection, then the evidence of the transition of *écoles* into greenstone on one side and stocks on the other, and the evidence of parallel unsqueezed greenstone inclusions in the porphyry must be taken as pointing to the troublesome conclusion that quartz-feldspar porphyry has metasomatically replaced greenstone or converted greenstone into syntectic porphyry, which is about the same thing.

Such a conclusion is troublesome because the mechanism of its causation is not at once apparent. The writer has shown the *école* phenomena in the field to a number of distinguished colleagues, all of whom have demurred at the suggestion that the porphyry lenticules originated *in situ*, and all of whom have intimated a preference for one or another of the above three refuted hypotheses. Under

the circumstances the writer cannot essay to present an explanation; but longer and more detailed study makes it incumbent upon him to proffer some sort of suggestion as to the *modus operandi*. With certain misgivings, therefore, the following thoughts are presented.

Analyses of greenstone and porphyry samples do and must vary so much as to make it absurd to attempt a quantitative estimation of any supposed reaction of conversion of the former to the latter; but it is an outstanding feature of their comparison that the greenstone in general contains more magnesia, iron, carbon dioxide, and water, and less silica and alkali than the porphyry. It is therefore probably safe to infer that a reaction of conversion would require enough free energy in the form of magmatic superheat to infuse silica and alkali, and expel iron and magnesium together with carbon dioxide and water. If this could be brought about, the silica and alkali moving from the porphyry into the greenstone, and the iron, carbon dioxide, and water moving away from the vicinity to other lodging places in the country rock, then the transformation might be accomplished by fusion or metamorphism.

This proposal raises several questions, chief among which are these: (1) Would the presence of 2 or 3 per cent carbon dioxide and 3 or 4 per cent water in greenstone sufficiently reduce its fusion temperature to make it easily succumb to such superheat as the magma might reasonably be supposed to carry? (2) After such fusion, would the water and carbon dioxide tend to be confined by the diffusion law of Soret to the margin of the magma body, to accumulate there and form an increasingly attenuated hydromagma, occasionally further diluted by chance accessions of water from deep fissures? (3) Might the principle of Soret together with the ready consumption of silica and alkali at the locus of fusion co-operate to induce a migration of these substances from all parts of the porphyry magma toward the margins? (4) Supposing these things to occur and the magma to come to rest through the compensation of its propelling force, would the congealment temperatures of successive zones, in order of distance from the core of the mass, be progressively lower on account of increasing proportions of water and carbon dioxide? (5) If the congealment gradient is a steeper curve than the actual temperature gradient, would not the crystallization begin at the core and

terminate at the margin of the stock instead of following the usually assumed reverse sequence, thus forcing the excess alkali and silica outward by stages from one point of congealment to another so that all crystallization would occur in the presence of a sufficient amount of these substances to form a uniform eutectic, the resorbed quartz phenocrysts, perhaps, not being incompatible with this on account of the expulsion of excess substances just before the congealment of the ready-formed eutectic? (6) Would iron and magnesium migrate off as their carbonates in solution to some point in the country-rock background, perhaps finding lodgment by replacing the greenstone to make a ferrodolomite-sericite schist to stand as a witness to the process in just such satellitic situations as the derelict aureoles already described? and (7) Would not the *écoles* and the syntectic porphyry with its parallel inclusions of greenstone have originated at this concluding stage of intrusion through these supposed migrations of heat and material?

These questions do not exhaust the points of doubt. Two important ones still remaining are the questions as to the difference between solution and fusion in the case of a hydromagma and the difference between these states and metamorphism where the hydromagma is very rich in water and the temperature is relatively low for a magma—perhaps around 400° C.

The nature of these vital questions makes it obvious that too many unsubstantiated assumptions would be involved in the required explanation. However, perhaps it would be permissible to intimate that the crux of the problem may be in the relation between the gradient of congealment temperatures and the actual temperature gradient, it being admitted that if the former were the steeper of the two, congealment would begin at the core of the stock and move outward, being superseded beyond the zone of fusion by a wave of molecular rearrangement and replacement.

CONTRIBUTION TO THE GEOLOGY OF SOUTHEASTERN OREGON (STEENS AND PUEBLO MOUNTAINS)

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ABSTRACT

In this paper the writer makes contributions to the geology of that little-known region of southeastern Oregon in which Steens Mountain and the Pueblo Mountains are situated, and which was discussed in a reconnaissance way some years ago by I. C. Russell in connection with ground-water resources. The material presented here is to be taken in the light of additional contributions, and not as an exhaustive treatment.

The main theme is the structure of Steens Mountain, which is discussed in some detail and the general conclusion expressed that this so-called "fault block" mountain and accompanying *graben* owe their origin to thrust and not to normal faulting.

New evidence for former glaciation on Steens Mountain is presented, thus strengthening the thesis of Russell.

A first attempt at a compilation of a stratigraphic table for this region is given, and the tuffs at the base of the Steens Mountain Valley are tentatively correlated with the John Day tuffs of Oligocene age, farther north.

INTRODUCTION

Southeastern Oregon may be considered in general as all that portion lying south of the Strawberry Range (a spur of the Blue Mountains) and east of the Cascade Mountains. It comprises chiefly the counties of Klamath, Lake, Harney, and Malheur, in order, from west to east. This region is, for the most part, one of large shallow lakes and playas and of interior drainage, being the northernmost portion of the Great Basin.

This paper is concerned principally with that part of the area of which Steens Mountain and the Pueblo Mountains are the center, i.e., the southeastern corner of Harney County near the Oregon-Nevada boundary (Fig. 1).

Our chief sources of published information concerning the general region are the early papers of I. C. Russell[1] between the years 1884 and 1905, and the two excellent studies in economic geography by Gerald Waring[2] in the "Water Supply Series" of the U.S. Geological

[1] *U.S. Geol. Survey Bull. 217.*

[2] *U.S. Geol. Survey Water-Supply Papers 220, 232.*

Survey. These last two papers leave little to be said with reference to some phases of the general geology and geography of that region. For a most illuminating discussion of the physiography of Steens and Pueblo Mountains we are fortunate to be able to turn to a paper

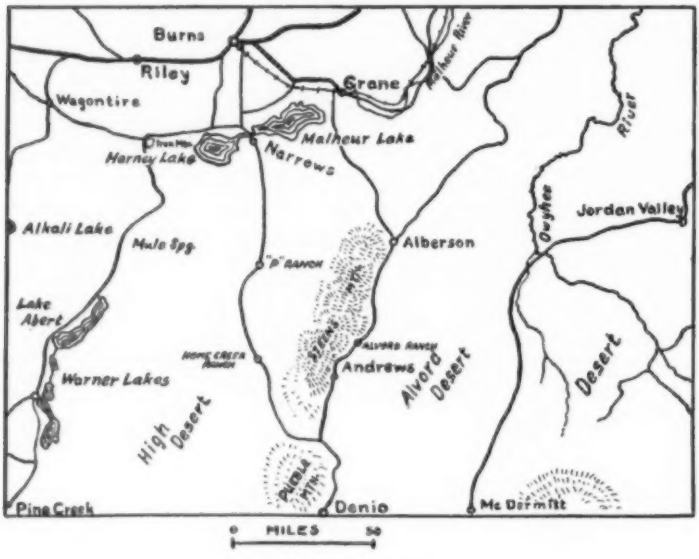

FIG. 1.—General location map

by W. M. Davis[1] published twenty-five years ago. As a result of the work of Russell, Davis, and Waring, the broad outlines of the geology of that region have been sketched, and now it remains merely to fill in the details. The present paper is intended particularly to discuss the structural geology in the light of additional data and add certain geological details lacking in the papers mentioned.[2]

The field work in this territory was carried on during several

[1] "The Mountain Ranges of the Great Basin," *Bull. Museum of Comp. Zoölogy*, Vol. XLII (1903), pp. 129–77.

[2] The present writer has recently contributed to the literature on the economic geography of this region. This material will be found in the series of chapters on *The Physical and Economic Geography of Oregon*, chap. xi, "Commonwealth Review of the University of Oregon," Vol. VIII, No. 2 (1926).

weeks in 1923 and 1924. Owing to the shortness of the time in the field, it was not possible to exhaust the subject, but enough was done to enable some fairly interesting contributions to be made.

GENERAL

The physiography of this region has been sketched by the writers just named. For purposes of orientation, the writer will give a brief summary of the geologic and physiographic history and of the broad structural features of southeastern Oregon.

GEOLOGIC AND PHYSIOGRAPHIC HISTORY

We have very few clues concerning events in southeastern Oregon prior to the outpouring of the Columbia lava. We cannot tell as yet the age of the Pueblo Mountain crystalline rocks, but they appear to be older than the Tertiary. That there was a period—or periods—of intense deformation in this part of the territory is proved by the schists at the southern end of the Pueblo Range.

However, one of the great, if not the greatest, geologic events of this region was the outpouring of the vast Columbia lava flows which veneered and modified the pre-existing topography. From what can be seen and studied within the confines of this particular province, one cannot complete the story of these events. It is necessary to go to the border zones, or even well outside, to get the proper clues. But in the upper course of the Deschutes River and the lower part of the Crooked River one finds a record which, in the main events at least, must hold true for much of the area now covered with lava through which the High Plateau streams have not yet cut.

According to Russell, there were five main chapters in this record, which have been outlined in his discussion relating to the Deschutes River. Prior to the deposition of the Columbia lava, there was extensive erosion of the older land masses, leaving monadnocks such as the Coyote Hills, Wagontire Mountain, and Pueblo Mountains standing well above a probable peneplain of Eocene age. On this old surface, now in topographic unconformity with the later lava surface, there were vast accumulations of volcanic ash interbedded with lake deposits and eolian sands. There was erosion of these and subsequent filling of the old valleys with lava flows and

later a partial exhuming of the older topography. However, the present and older drainage lines do not always coincide, and the present valleys are not as extensive as the earlier ones. These points are all clearly shown at various places in the upper Deschutes and the lower Crooked River. This lack of topographic adjustment is marked.

During or shortly following this great outflow of lava there was considerable elevation of the region, accompanied by gentle folding and extensive faulting. These movements have undoubtedly continued until very late, since the erosional modification of the original dip slopes of such blocks as Steens and Warner mountains has been slight.

In various papers on the Basin ranges outside of Oregon, reference has been made to old surfaces cutting across these faulted structures. The writer has found no evidence in this part of Oregon for any postfaulting peneplaination. Not one of the four major criteria for this event in the latter part of the region's history can be brought forward, and therefore Baker's[1] reference to the physiographic evidence for postfaulting peneplaination cannot be extended to this part of the Basin Range Province.

As this region became more elevated and the general Pleistocene changes developed, alpine glaciers at least 5 miles in length were formed on the north and south sides of Steens Mountain and these modified to a certain degree the topography at altitudes above 9,000 feet. Russell called attention to the evidences for glaciation in Kieger Canyon (Fig. 2) on the north side, but did not mention any glacial phenomena in the Wildhorse and Blitzen canyons. He also was not very positive in his conclusions, and apparently felt the need for more evidence on the subject. Hanging valleys, U-shaped valleys, and cirque lakes are all to be found there. Glacial modifications, morainal material, truncated spurs, and rock steps are found at least 5 miles from the summit in the Wildhorse as well as in the canyon studied by Russell.

During and at the close of the Pleistocene glaciation there was much more water in the country than now. This is shown by the many great gravel accumulations, such as those at the south end of Abert Lake. This excess of water was due, doubtless, to the melting

[1] *Jour. Geol.*, Vol. XXI, No. 3 (1913).

of the alpine glaciers on such high places as Steens Mountain, and also, perhaps, to a general heavier precipitation at that time. At that time, also, the lakes of the region were many times their present size. Since the melting of the glaciers, which no longer exist anywhere in southeastern Oregon, there has been a gradual desiccation of the region as a whole, and today many former lakes are nothing more than playas. With the diversion of many streams for irrigation purposes, and the sinking of many wells, the natural desiccation has been aided, and now these lakes are rapidly decreasing in

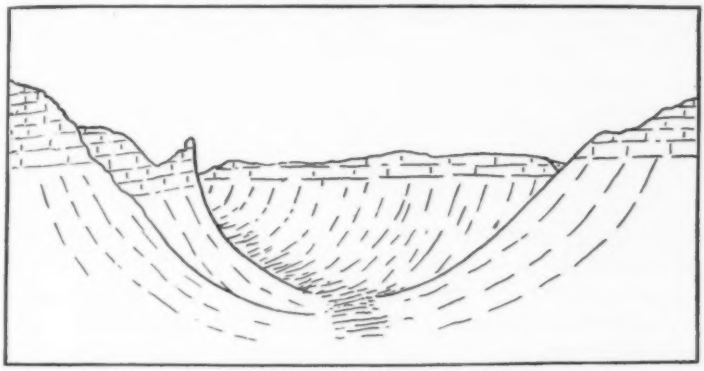

FIG. 2.—U-shaped valley (due to glaciation) of Upper Kieger Canyon

size, while some, like Silver Lake, have completely dried up within the last decade. The two largest survivors of the Pleistocene lakes, Harney and Malheur, were, in the summers of 1924, 1925, and 1926, almost "bone dry"—a phenomenon in the case of Harney Lake at least not noted for the past thirty years. Goose Lake, another of the large remnants of the larger Pleistocene lakes of this region, so dwindled in size during the past season that deep ruts of earlier wagon tracks across its beds (thought by some to be those of the great emigrant trains of 1852 and later, when another dry cycle was on) were revealed.

To what extent eolation, or desert wind erosion, has modified the topography of the region, we can only conjecture, for no definite records of its action have yet been found. The major work of the

wind in southeastern Oregon is that of deposition, and what wind erosion there is does not appear appreciably to affect the older and harder formations. Typical wind-erosion features, such as differential sculpturing of the rocks, are not pronounced. This seems to be one of the most serious weaknesses in the argument for the importance of eolation. Of course, in other parts of the Basin Range Province wind-erosion features may be more in evidence.

The material making up the chief load of the wind is undoubtedly derived from the tuffs and intercalated sands below the great basalt member, and possibly in part from the Payette (Eocene) sands so widely distributed to the northeast and east of this region. As deflation of the harder formations like basalt depends upon weathering, and this appears to be a rather slow process in this dry region, it seems that little of this wind-borne material can come from the basalts.

STRUCTURE

The structure of this region has hitherto been thought to consist in the main of normally faulted blocks of lava terrane tilted at various angles so as to give block mountains of different heights. Topographically these mountains consist of long gentle dip slopes on one side, with steep escarpments on the other. The structure, however, is more complicated than appears from superficial examination. In addition to the extensive faulting, there is also folding, as evidenced by the wide low anticlines and shallow synclines. Catlow Valley is due to the sag of the formations between Warner Mountain and Steens Mountain. A well-marked low anticline, as noted on Waring's map, can be seen just east of Diamond Craters, a few miles to the northwest of Steens Mountain. Practically nowhere in this region do we see simple homoclinal blocks. Only a cursory view of the country would lead to the description of these structures as merely tilted blocks. They are folded, tilted, and warped.

One striking feature of the region is the so-called *graben*, where the center of the arch is supposed to have dropped down, leaving a flat-bottomed trench between two upstanding walls. In these undrained, down-faulted areas or *bolsons* water has collected, forming lakes. The Warner lakes are typical. In the Steens Mountain region there were similar lakes, but they are now nothing more than playas.

STRATIGRAPHY

Since none of the earlier writers attempted to tabulate a stratigraphic summary of the geologic formations in this region, the present writer has compiled such a summary in Table I, principally from the work of Waring and himself.

The placing of the Steens Mountain basalts in the Columbia lava series is open to some question, since we have no definite horizon above, like the Mascall (Middle Miocene) of the John Day region, to delimit them accurately. Their great thickness and the superficial resemblance to the Columbia lava, and the presence of the Lower Miocene Trout Creek formation, have led to the provisional correlation.

With this very general outline of the physiography and geology of the region as a background, let us now consider Steens Mountain in particular.

STEENS MOUNTAIN

LOCATION

Steens Mountain lies in the southeast corner of Harney County, whose south line is the Nevada state line, and whose eastern boundary is separated by only one county, Malheur, from the Idaho line. The mountain is a long fault block of Tertiary lavas and tuffs, tilted gently to the west, with a steep escarpment to the east. It extends from about the north line of T. 31 S., R. 35 E., to about R. 31 E., and it comprises roughly 500 square miles of territory.

TOPOGRAPHY

It is, at the highest point on its eastward escarpment, only a few feet under 10,000 in height. In the extreme western portion it merges into the Catlow Valley and the valley of the Donner and Blitzen, with only a low escarpment between it and the valley floor. The general tilt of this block in the lower western portion is from 5 to 10 degrees. Nearer the eastern crest the lava beds are sharply upturned at an angle of about twenty degrees, though the angle is less at the crest of the block.

Steens Mountain is remarkable in many ways. On its long westward gentle-dip slope, the surface over large areas seems not to have been changed in any notable respect since the mountain was formed.

The slope is so gentle in the regions of Smith's flat (Fig. 3), and so little affected by erosion, that one can gallop a horse over it at will. However, this comparatively untouched surface, which clearly seems to be the original surface, is deeply incised in several places by almost perpendicular-walled canyons of great depth. The most

TABLE I*

TENTATIVE TABLE OF STRATIGRAPHY

Age	Formation Name	Thickness	Lithology	Attitude	Type Locality
Recent	Alkali	1″–15′+	Sands and gravels Salt incrustations Loose sands	Alluvial fans, etc. Calderas Dunes	Alkali lake
Recent or Late Pleistocene	Diamond		Basalt flows and scoria	Flows	Diamond craters
Pleistocene	Wildhorse Chewaucan Fossil Lake	Varying 25′–100′ ?	Sand and gravel Glacial Moraine Oxidized gravel Lake silt	Approximately horizontal Horizontal	Kieger Canyon Lower end Chewaucan marsh Fossil Lake
Pliocene	?	20′–50′+	Basalt and rhyolite	Vertical dikes and capping	Steens Mountain (dikes)
Miocene	Columbia lava	2000′+	Basalt flows	Gently folded and faulted on great scale	Columbia Gorge
Lower Miocene	Alvord	1000′+	Coarse tuffs and interbedded sands	Below and apparently conformable with lava	Steens Mountain (John Day?)
	Trout Creek	?	Fine white ash with plants		Trout Creek Flagstaff Butte
Eocene (?)	Coyote	1000′+	Older andesite, rhyolites, and andesitic tuffs	Massive effusives	Coyote Hills
	Wagon tire	?	Rhyolite	Effusives	Wagontire Mountain
Mesozoic or Older	Pueblo	?	Crystalline rocks Porphyries, schists, etc.		Pueblo Mountains

* Compiled by Warren D. Smith.

notable of these are the Kieger, McCoy, and Blitzen on the west slope. Wildhorse Canyon, in which the stream flows due south from near the summit, is somewhat different in nature and appears to have followed a secondary fault line parallel to the main fault which marks the eastern escarpment of the mountain. As one stands on the very gently sloping and fairly even summit of this mountain he is unaware of the tremendous gorges that these streams have cut into this original surface. Even the U.S. Geological Survey map, com-

piled by G. A. Waring in 1898, and an excellent map in general, does not reveal all of the unique features of this topography. Particularly at the summit these various tributaries before mentioned, and the

FIG. 3.—Steens Mountain—Smith's Flat

shorter and swifter ones on the eastern escarpment, have worked back in such a way that the plan of the crest of the mountain is much more irregular than is shown on this map. These tributaries

FIG. 4.—Eastern front of Steens Mountain

do not head opposite one another, but are offset, and this has given a rather serpentine outline to the summit.

The eastern escarpment (Fig. 4), is very interesting and quite

different from the notable Abert and Warner escarpments farther to the west. These latter are fairly straight walled, at least in the upper part, with the normal talus curve at the bottom, but the Steens escarpment is not so regular and is far more rugged. The two profiles are given in Figure 5 for comparison. The modification of the usual profile in the case of Steens is undoubtedly due to the presence of a thousand feet of tuffs at the bottom of the section. Also the topography is further modified by fault slumping. The contrast between the eastern front of this mountain and the dip slope to the west is one of the most remarkable features in this region.

It is also worthy of note that in this region practically all the profiles seen were of the concave (upward) type, as in (*a*) of the

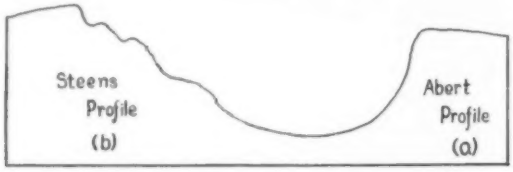

FIG. 5.—Comparative profiles of Steens and Abert escarpments

above figure. These are normal desert profiles, in striking contrast to those of a humid region like that of western Oregon.

STRATIGRAPHY

In the best section of Steens Mountain, namely, the eastern escarpment, where nearly 5,000 feet of rocks are exposed, the complete stratigraphy of this mountain can be made out almost at a glance. The first thousand feet from the valley floor are made up of tuffs and intercalated sands, dipping westward, apparently conformably with the overlying lavas. These tuffs vary from very fine to coarse grained, and are buff colored to whitish. Differentiated from these with difficulty are the layers of more or less fine sand. Some of these may be wind-borne material; some appear to be fine lake sediments. As a rule these deposits do not show much induration. Indeterminable vertebrate bone fragments, which of course are of little value as index fossils, were picked up in the talus of these tuffs.

Russell, in his water-supply investigations, mentioned sandstone in this mountain, but the present writer saw no sandstone in the Steens section. What Russell must have referred to as sandstone is tuff with intercalated loose sands.

On the basis of general position and lithology, neither of which is conclusive evidence, we may provisionally correlate the tuffs below the Steens lavas with those below the Columbia lava in the John Day section, and in the Deschutes Canyon, and finally with those noted by the present writer below the basalts of the Cascades in the Santiam[1] section on the western slope of the Cascade Range. Above this series there are nearly 4,000 feet of lava in flows very much as in typical Columbia lava sections, as in the Deschutes and Columbia gorges.

A suite of specimens, the first ever to be studied petrographically from this mountain, as far as the writer knows, was collected at various points on the mountain, principally from Wildhorse and Kieger canyons near the summit and a few from the top of the mountain. These petrographic descriptions will be reserved for another paper, but it may be stated here that they show that the lavas forming portions of the mass of this mountain are in the main coarse-grained basalts with some diabasic facies. Some rather striking specimens containing quite unusual phenocrysts of labradorite nearly 2 inches in diameter were obtained. The result of the determinations made so far indicates that we have here a series of lavas much like the traps of the Thulean Province of the North Atlantic reviewed by H. S. Washington in his study of Deccan traps and plateau basalts.[2] Although this study will have to be supplemented by examination of more specimens from eastern Oregon in order to prove the case, we apparently have another bit of evidence against the alleged sharp distinction between the Atlantic and Pacific rock types.

At the Diamond craters, a few miles to the northwest of Steens Mountain, pahoehoe basaltic lava is found over an extensive area where it issued very recently (perhaps within five hundred years). The craters are still quite fresh looking. In view of such vents as

[1] *University of Oregon Bull.*, new series, Vol. XIV, No. 16 (December, 1917), p. 37.

[2] *Bull. Geol. Soc. Amer.*, Vol. XXXIII (November, 1922), pp. 765–804.

these and the dikes seen in the eastern face of Steens Mountain, we can be quite positive in our conclusions as to the formation of the great eastern Oregon lava flood. In the first place, what is known as the Snake River or Columbia lava is a composite of many floods; and second, it came from many vents, some more or less local and circular, while others were linear fissures. While these are not new observations, it is important to emphasize these points, since the textbooks usually stress the fissure type of eruption in speaking of these northwest lavas.

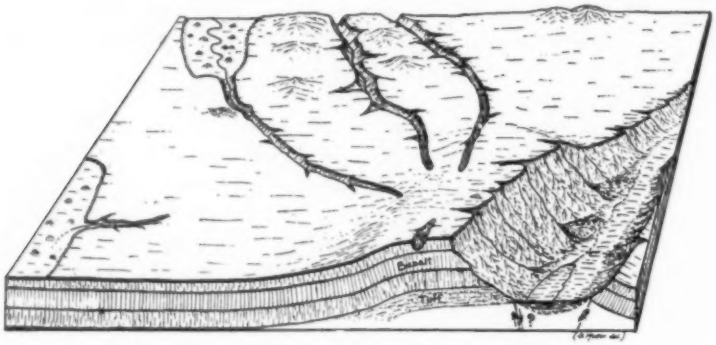

FIG. 6.—Block diagram of the Alvord Valley *graben*

Later materials, not always topographically higher, are the talus deposits at the foot of the Steens escarpment and the small accumulations of gravel wash in the higher reaches of the canyons of Steens Mountain. In the Wildhorse Canyon, especially, considerable accumulations of morainal material were found at about 5 miles from the summit, indicating approximately the lowest limit of the movement of the ice in that particular canyon. This material was made up of loose angular bowlders, some well faceted. Striations are rare, apparently because the material is poorly adapted to their preservation. Desert varnish has undoubtedly helped to obscure any markings of this kind that may have existed. These blocks are largely of basalt, ripped off the canyon walls and the valley floor as the ice moved downward.

STRUCTURE

The visible structure of Steens Mountain appears at first fairly simple. It apparently is a great homocline to the west, and represents a true fault-block mountain (Fig. 6). However, on the eastern side of the Alvord Desert, immediately east of Steens Mountain, there is an escarpment of basalt facing west, with a long gentle slope to the east. If this be interpreted as the continuation of the Steens Mountain structure, then the whole structure is that of an arch with the keystone broken and *apparently* dropped down. This eastern limb of the anticline is not as pronounced or as striking in appearance as the west limb; the anticline is thus asymmetrical.

Another point, already noted in Steens Mountain, is that near the summit, particularly on the west wall of Wildhorse Canyon, at about 9,000 feet, the lavas for a short distance along the dip are tilted to an angle of some twenty or thirty degrees east, though the average lower down is about five degrees to the westward. The Steens Mountain block is therefore not a simple homocline.

The subject of Basin Range structure has recently been reviewed critically by Louderback[1] in "Basin Range Structure in the Great Basin." He very effectually disposes of the eolation theories of Keyes, and all the observations of the present writer in the vicinity of Steens Mountain substantiate Louderback's position.

The writer would call attention now to the theories of E. J. Wayland[2] advanced to explain the phenomena of the Lake Albert Rift Valley in East Africa, where superficial phenomena occur somewhat similar to those exhibited in this part of Oregon. The geologist of Uganda stipulates compression rather than tension as the principal factor in the formation of that part of the Great Rift Valley, and cites experiments on the compression of timbers, taken from Emmons, to reinforce his arguments. The results of this experiment are shown in Figure 7. A comparison of Gregory's and Wayland's ideas is given in Figure 8. It will be recalled that Gregory holds to the normal fault theory, which Russell, and later Davis, applied to the Steens Mountain and Abert Lake region of Oregon.

E. H. McAlister, professor of mechanics and astronomy, Uni-

[1] *University of California Pub.* (Geol. Sciences), Vol. XIV, No. 10, pp. 329–76.

[2] *Geog. Jour.* (London), Vol. LVIII, No. 5 (November, 1921), pp. 344–59.

versity of Oregon, has indicated to the writer that in an arch of this kind there would be little chance for a portion near the center to drop down. Tension in the upper portion of an arch changes with depth to compression which would make any such happening extremely improbable. He exhibited a piece of fir wood in which a deformation similar to that at Steens Mountain had been produced in the wood by compression at the ends (in this case vertically applied owing to the set-up of the machine). This is shown in Figure 9.

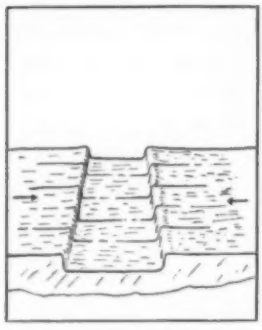

FIG. 7.—Result of the compression of oak beam simulating formation of a *graben* (after Emmons).

It will be noted in this experiment that the shear approximates 45 degrees in both sections. On Waring's map these great faults, such as those of Steens and Warner mountains, show a decided northeasterly trend, which would correspond to one of these shears.

Whatever may be said for Wayland's theory (and the writer is inclined to the same views), we can furnish little from the Steens Mountain region conclusively to prove it. The excessive accumula-

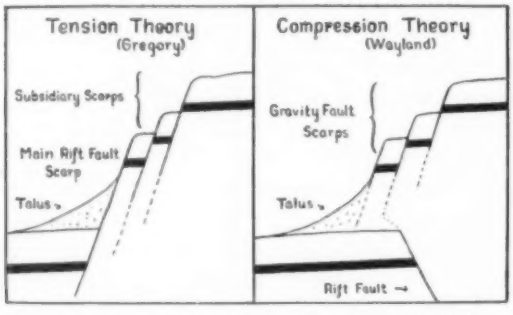

FIG. 8.—Comparison of tension and compression theory in the formation of rift valleys.

tions of talus pretty effectually prevent us from seeing what has happened lower down. Reverse faults may be there, but at present we have no way of proving or disproving them. However, in eastern

Oregon the bending of the lavas should be emphasized. They are not simply block faulted; they are arched as well.

In this connection it is interesting also to note a discussion by Charles L. Baker,[1] who came to the conclusion likewise that "the Basin ranges are really mountains of tangential compression. The evidence for this view is both structural and physiographic. . . . . " After giving some structural reasons for discarding the gravity-fault theory of Russell, Le Conte, and King, he stated: "The key to the problem is an old erosion surface, locally approaching the conditions of a peneplain. This bevels the folded strata, etc. . . . . " The present writer cannot assert that this physiographic argument applies in the Steens Mountain country, but he does agree with Baker in his views of the structure.

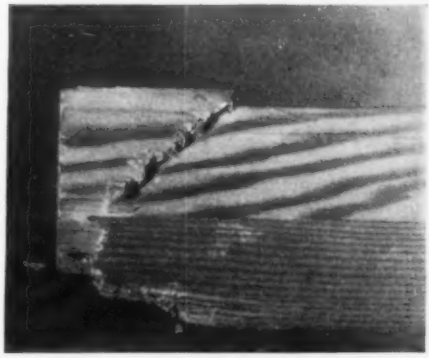

FIG. 9.—Result of deformation by compression of fir-wood beam (McAlister).

If the Alvord *graben* were formed by a portion near the center of the arch having subsided during the stretching (tension) accompanying the arching of the lavas in this region, we are at a loss to account for sufficient empty space for this central block to drop back into, unless prefaulting vulcanism had drained out material from beneath the arch. There is sufficient extrusive material in the country to allow for this, *if it came from beneath the Alvord graben.*

Still we are unable to explain the great and abrupt change in dip near the crest of the arch except on the basis of thrust. This abrupt increase in dip toward the summit seems to demand great tangential compression and not tension. Given a broad low arch with tension, there might be normal faults, as previously postulated in this region. But instead of the central part of the arch having gone

[1] *Jour. Geol.*, Vol. XXI, No. 3 (1913).

down, it seems to the writer more probable that the side walls of this *graben* have been forced up past the central portion.

Of course the best way to prove this would be to take some material, neither too plastic nor too brittle, and cause it to arch until it breaks, and then note what takes place. This very experiment has been carried out by Professor Jagger, and the result can be seen very clearly in Figure 143 of Professor Daly's new book, *Our Mobile Earth*. In this a *graben* almost identical with ours was the result of the two limbs of the anticline having been thrust up past the central portion, *which did not* drop down, but remained practically stationary *at its original elevation*.

On this point the writer would like to present for consideration the fact that the floors of the several *grabens* of the region are about the same elevation and do not fall below the general level of the country as a whole. Why do we not find these at different levels and why are not some considerably below the average elevation of the plateau? Why did they drop just so far and no farther?

Mr. Chester Washburne has recently advanced before the Cordilleran Section of the Geological Society of America (Los Angeles, January 29, 1927) some very interesting and promising new conceptions concerning the mechanics involved in faulted areas like the one under discussion. These seem to be quite acceptable to the present writer, but in advance of their publication we cannot discuss them further except to say that they further complicate the story and offer little comfort to those who adhere to older and simpler notions concerning these structures.

In summarizing the evidence against the explanation by tension with normal faulting we have apparently the following: (1) The structure of Steens Mountain itself. It is not a simple homoclinal tilted block. (2) Under compression, wooden timbers and other materials under the proper conditions have simulated the *graben* structure of Steens Mountain. (3) The approximately equal elevation of the "down-dropped" or *graben* areas. (4) Lack of evidence of a void below the arched rocks into which the central portion could drop. (5) No visible normal fault planes of any magnitude. (6)[1]

[1] The writer has recently had his attention called to the paper on keystone faults by W. O. and I. B. Crosby (*Bull. Geol. Soc. Amer.*, Vol. XXXVI, No. 4 [December.

From the simple mechanics of the problem, any material down-dropping of the central portion of an arch is apparently highly improbable.

One other query should be raised. We have accepted without question in the past the statement that these bold cliffs of Steens, Warner, and other similar mountains are fault scarps. What are the criteria for fault scarps? We are by no means clear on this point, and opinions vary. We shall probably find, as in so many instances, that faulting alone will not explain these, nor will wind erosion, as claimed by Keyes; and we may have to resort to all three: faulting, water erosion, and wind erosion, with the last as the least in importance. The importance of erosion by running water, in this problem, probably has been neglected. Torrential wash in a period of conceivably much greater humidity would, without question, accomplish much greater erosion than appears to be taking place in this region at the present time, which is an exceedingly arid stage of the climatic cycle. Evidence of a tremendously greater amount of torrential wash is abundant all through the adjacent country, particularly as shown by the vast accumulations of gravels in the Chewaucan Marsh south of Abert Lake and the large delta deposits near the town of Plush, west of the Warner lakes.

PUEBLO MOUNTAIN

LOCATION

Pueblo Mountain is located in the extreme southern part of Haney County, about 20 miles from the eastern boundary of the county, and extends over into the state of Nevada. It is topographically an extension of Steens Mountain, but in physiography and geology it is quite distinct from that mountain. A short discussion of this mountain is included in this paper for two reasons: namely,

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1925], pp. 623–40) which he had overlooked. At first it might seem as if there were something in the phenomenon described by these writers which would be contradictory to statement (6), but, as these observers clearly point out, the mechanics of *grabens* and of keystone faults are essentially different. The present writer contends that there has been something more than simple stretching in the Steens Mountain structure, as indicated by the relatively high angle of dip as one reaches the crest of the mountain. Furthermore, we do not have any evidence of parallel joints or any simultaneous movement along such if they could be located.

on many maps it does not appear at all, and very little is known about it even by persons living in Oregon; and, second, when shown on maps at all it is usually represented as an extension of Steens Mountain. The boundary between the two is, roughly, at the pass between Catlow and Alvord valleys, which traverses Ranges $32\frac{1}{2}$ and $32\frac{3}{4}$ E., T. 37 S. This mountain is in part shown on the topographic map accompanying *Water Supply Paper 231* by Gerald Waring, made in 1908. The writer has completed the topographic sketch of this mountain left blank by Waring. The mountain is in

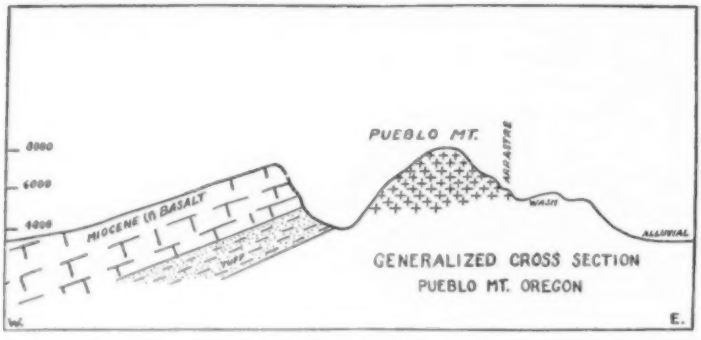

FIG. 10

general about 25 miles long and from 5 to 10 miles wide, and is a trifle over 8,000 feet in elevation. The presence of several gold and copper prospects on the slopes of this mountain make it of more popular interest than Steens Mountain. However, the writer's recent examination of the prospects revealed no deposits of especial merit, and owing to several unfavorable economic factors, they have a questionable value.

The first reference in the literature to this mountain is by William Blake,[1] an early eminent mining engineer, who very briefly described the Pueblo Mountains in Nevada as long ago as 1876. Davis, in the paper already cited, discussed Pueblo Mountain in relation to Steens Mountain and gave some valuable notes on its physiography, including a sketch of it.

[1] *Proceedings California Academy of Science*, Vol. V (1875), pp. 210–14.

TOPOGRAPHY

This distinct orographic unit consists of a single range trending generally north and south. Its topography indicates the nature of the materials that compose it; igneous intrusives and metamorphics. Because of the great differences in the nature and age of the materials, it is in decided topographic contrast to Steens Mountain, being physiographically much older than the latter. Although it rises rather abruptly from the Alvord bolson, the profile is quite different from that of Steens. Although fairly steep slopes are found, they are convex curves. These slopes, too, are scored by small wet-weather insequent streams. A geologic cross-section of this mountain and its relation to the Miocene lavas are shown in Figure 10. The lava flows to the west of Pueblo Mountain, which are a continuation of the Steens Mountain block, are seen dipping in a great monocline to the west, and if these were projected upward in the direction of their slopes they would pass over Pueblo Mountain. Whether the Pueblo massif has been brought to the surface largely through erosion, or through a combination of faulting and erosion, does not yet seem to be clear.

GEOLOGY

As there is practically no literature on Pueblo Mountain other than the short notes by Waring and Davis, so far as the writer has been able to ascertain, he will quote first from these and then give his own notes. Waring says:

> Pueblo Mountain and the range south of it are composed of rocks that belong to an older series than do the lavas to the north. These mountains were only cursorily examined, but from float specimens that were collected along the eastern base of the range they appear to be made up of andesitic porphyries, micaceous schists, and granitic rocks, which have been more or less extensively affected by mineralizing agents.
>
> In a paper published in 1875 by Dr. James Blake, he describes the southern extension of these mountains in Nevada. There he found micaceous and talcose schists and metamorphic limestones, which dip away from the mass of porphyry that forms the crests of the eastern ridge of the ranges.
>
> The rocks of this range are the oldest that were noted, but to what earlier period than the lavas they belong, there are no facts at hand to suggest.

This general description of Pueblo Mountain by Waring and Blake is in the main correct. The rocks of this range, stated by

Waring to be the oldest noted in this region, are certainly the oldest which the writer has seen. With reference to this mountain, the present writer recorded the following notes:

> The axis of the mountain trends north and south. In its lower portion the mountain is made up largely of fine-grained aphanitic rock, almost a greenstone, cut by numerous large dikes of feldspar porphyry, with phenocrysts of feldspar one inch in width in some cases. It was difficult to make out any definite trend of these dikes, but in general they were northeast and southwest. Large veins and masses of a white quartz abound. Veins being worked by Douglas Brown, a local prospector, are smaller and carry quite a number of copper minerals. The best vein seems to trend east and west, dipping to the south (angle of dip about fifty degrees), and is 3–4 feet wide. There are other smaller veins dipping at low angles to the north and northwest. *No plutonic rocks were seen.*

As one travels southward toward the California line and beyond, the dominant rocks are mica schists.

An ascent to the summit of this mountain was made. The surface rock on the summit is a hard, dense porphyry, with a decided ring when struck with the hammer, which has broken up under the extreme temperature changes into many small blocks and slabs. The mountain top is fairly level for a few acres, and quite bare of trees.

Petrographically, the rocks on Pueblo are quite distinct from those on Steens Mountain, indicating still further the dissimilarity between these two mountains which are superficially connected.

A STRUCTURAL AND PETROGRAPHIC STUDY OF THE GLASS BUTTES, LAKE COUNTY, OREGON

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ABSTRACT

The Glass Buttes, a small mountain range composed entirely of volcanic rocks, have as their dominant structural feature an anticline. This anticline has been very greatly modified by a multitude of normal faults. The lavas of the district represent three periods of extrusion. The older flows of basalt were followed by a series of acidic lavas which were, in turn, partially covered by a later series of basalts.

INTRODUCTION

The Glass Buttes are a small mountain range rising out of the rather featureless sandy desert of northern Lake County, Oregon. Although minor in size in comparison to the fault-block ranges of southern Oregon and Nevada, this range has received a certain amount of attention owing to the occurrence of considerable quantities of black and variegated obsidian within its borders.

The Glass Buttes were visited by I. C. Russell in his early reconnaissance in southern Oregon.[1] Concerning this locality Russell stated: "The Glass Buttes were found to be composed of rhyolite, together with large quantities of obsidian, or volcanic glass. No evidence that they were once volcanic craters was observed; and no basaltic overflows, or other phenomena, were seen to indicate that they had recently been centers of volcanic action." In a later publication[2] Russell appears to have confused the Glass Buttes with one of the numerous volcanic craters that he had studied in this district, for he mentioned them as "remnants of ancient rhyolitic or andesitic volcanoes, now deeply dissected by erosion."

Pirsson noted the occurrence of obsidian[3] at this locality in his

[1] I. C. Russell, "A Geological Reconnaissance in Southern Oregon," *U.S. Geol. Survey Annual Report 4* (1884), p. 440.

[2] I. C. Russell, "Preliminary Report on the Geology and Water Resources of Central Oregon," *U.S. Geol. Survey Bull. 252* (1905), p. 49.

[3] L. V. Pirsson, "Rocks and Rock Minerals" (1st ed., 1908), p. 268.

text (published in 1908), and reference to its occurrence here was made in various other papers and texts of later date. Careful search of the literature, however, has failed to reveal the placing on record of any definite information as to the character and composition of the lavas of this region, and it is for this reason that this paper is presented as an addition to the somewhat meager knowledge already in existence concerning the great volcanic field of south-central Oregon.

STRUCTURE OF THE GLASS BUTTES RANGE

The Glass Buttes Range rises abruptly out of the desert plateau in the vicinity of the post-office of Rolyat and trends away to the southeast in a shallow arc, dying out in a low range of hills about 22 miles from its western beginning. Its greatest width is reached about 4 miles from the western end of the range, where a small transverse ridge causes a maximum extension of about 8 miles. In general it is about 6 miles from one side of the range to the other. The range rises about 1,900 feet above the surrounding plateau, which, at this locality, has a general elevation of between 4,000 and 5,000 feet.

The Glass Buttes consist entirely of volcanic rocks representing three periods of extrusion. The first flows were olivine and augite basalts. These early flows were covered by a conformable lava series in which such petrographic types as augite andesite, quartz andesite, hypersthene dacite, augite dacite, hypersthene-augite dacite, perlite, obsidian, and vitrophyre have been found. This series is in turn covered, on the plateau adjoining the range, by very recent flows of olivine and augite basalt.

When viewed from the crest line of the Glass Buttes Range, the lava flows can be seen to tilt away at rather steep angles on either side until they flatten out and join the horizontal plateau below. The dominant structure of the range is known from these relations to be an anticline, and the range is similar in this respect to the anticlinal mountains that form the eastern spurs of the Cascades in Washington[1] and Oregon. Minor topographic irregularities of the range, however, are due mainly, not to the erosion of this anticline, but to a complicated system of normal faults which traverse the

[1] Anticlinal ridges of this type are specially well shown in the Ellensburg Folio, Washington, of the *Geologic Atlas of the United States*.

structure. The top of the anticlinal arch has been dropped into a *graben* which forms a great longitudinal valley in the very heart of the range. This central valley extends throughout the entire eastern three-fourths of the uplift. Small transverse *grabens* intersect this larger one and there is a profusion of small normal faults and fractures on the sides of the anticline. Numerous small faults also occur on the floor of the plateau adjacent to the range, and their uneroded scarps can be seen winding across its otherwise featureless surface. Field evidence indicates that the faults are purely tensional, and not compressional. The anticlinal sides of the main *graben* valley are also cut by normal faults.

The multiplicity of very small normal faults and fractures is perhaps the most interesting phenomenon in the structure of the Glass Buttes. These small faults are extremely numerous. Their throw in few cases exceeds 50 feet, and there are many examples of slips of 10 feet or less. Small minor faults seem to be characteristic of the very recently faulted blocks of southern Oregon. D. W. Johnson[1] quotes Dr. G. K. Gilbert as stating that in the Klamath Mountains reconstruction of the pre-faulting surface would be a difficult task, because the great fault blocks have been "intricately sliced and dislocated on a small scale; and one of the marvelous features of the region is the association of major faulting with elaborate contemporaneous minor faulting."

Major faults also occur in the Glass Buttes. The largest throw measured on any one fault exceeds 1,000 feet. There are, however, in this portion of central Oregon no vast fault escarpments such as those defining the eastern slope of Steens Mountain or the westward-facing wall of Abert Rim.

Mountain ranges with a faulted anticlinal structure similar to that of the Glass Buttes are common throughout southern Oregon. Steens Mountain, the Warner Ranges, and Winter Rim furnish examples. They are seen to be the northern extension of the fault-block ranges of Nevada. The exceedingly uneroded character of the fault scarps in Oregon, in contrast to the somewhat dissected ones of Nevada, suggests that the faulting in southern Oregon, while fol-

[1] D. W. Johnson, "Block Faulting in the Klamath Lakes Region, Oregon," *Jour. of Geol.*, Vol. XXVI (1918), p. 236.

lowing the same structural lines as that to the south, was of later date. In the Glass Buttes region minor faulting affects a series of lava flows so recent in origin that vegetation appears to have only lately gained a foothold upon them. Faulting of post-Lahontan date is described by Russell[1] as occurring in northwestern Nevada. From these considerations it would seem probable that a considerable portion of the minor faulting of southern Oregon does not date back of the Pleistocene.

PETROLOGY OF THE GLASS BUTTES

THE YOUNGER BASALTS

Three series of lava flows of different periods of extrusion occur at the Glass Buttes. The youngest of these is a series of basaltic lavas so recent in age that the flows still preserve their original surface features although they have been covered with a few inches of transported soil. This series of lava flows appears to have been erupted contemporaneously with the faulting in the Glass Buttes district, for not only do these lava flows lap up against the main fault blocks of the Glass Buttes Range, but they are in turn cut by other faults of slight displacement.

Evidences of recent vulcanism are widespread throughout southern Oregon and central Idaho.[2] Many of the recent basaltic eruptions have been described by I. C. Russell and by other authors; and, in fact, these recent volcanic products have received more attention than the much thicker and more widespread lavas of earlier age that occur in central Oregon. Famous localities of very recent basaltic lavas are the craters of the Moon District in Idaho and the Jordan craters in southeastern Oregon. These eruptions were apparently of a very viscous type characterized by ropy surfaces.[3] Unfortunately little has been published of strictly petrographic nature concerning

[1] I. C. Russell, "Geological History of Lake Lahontan, a Quaternary Lake of Northwestern Nevada," *U.S. Geol. Survey Monograph 11* (1885), p. 282.

[2] I. C. Russell, "Notes on the Geology of Southwestern Idaho and Southeastern Oregon," *U.S. Geol. Survey Bull. 217* (1903), pp. 36–58; Gerald A. Waring, "Geology and Water Resources of the Harney Basin Region, Oregon," *U.S. Geol. Survey Water-Supply Paper 231* (1909), pp. 22–23.

[3] Henry S. Washington, "Petrology of the Hawaiian Islands; IV. The Formation of AA and Pahoehoe," *Amer. Jour. of Science* (3d series), Vol. VI (1923), pp. 409–23.

these basalts, the principal aim of previous workers having been to place on record descriptions of the surface features of the lava flows and of the bombs and ejectamenta from the craters, irrespective of the composition of the magma involved.

Cinder cones.—In the area of the Glass Buttes recent lavas occupy a portion of the plateau directly to the north of the central portion of the range. They are probably represented at other nearby localities on this plateau as well. From the summit of the Glass Buttes several small cinder cones can be seen, all but one of which appear to be at least 20 miles from the range. This nearer cone, situated a few miles north of the central portion of the range, rises from 200 to 250 feet above the level of the plateau and has a circumference of a little less than a quarter of a mile at the crater lip. It is composed of small lapilli, bombs of various size and shape, and large blocks of solidified lava that have apparently been broken loose from below and ejected from the crater. The southwestern side of the cinder cone is lacking. However, if this portion of the cone was breached and carried away by an excessive flow of lava, showers of ejectamenta have since covered the lava filling which originally occupied the breach.

On the western side of the cone a small wall-like mass extends with a gentle slope from the lip of the crater to the plateau below. It has the appearance of a thin, uneroded dike, but examination reveals it to be composed entirely of lapilli and "driblet lava," from which it seems probable that this ridge represents a fissure extending out from the cone along which numerous "driblet cones"[1] or "ovens"[2] were developed which have since been broken and fragmented.

Recent lava flows.—It is probable that the majority of the basaltic flows that cover wide areas of the plateau in the vicinity of the Glass Buttes belong to the same period of eruption as the cinder cone, but they cannot be separated petrographically from an older series of basalts, and can only be determined stratigraphically when an intervening series of acidic lavas is present.

Two flows can be definitely correlated with this period of vulcan-

[1] J. D. Dana, "Characteristics of Volcanoes," 1891, pp. 17, 71, 85, 147.

[2] I. C. Russell, "Notes on the Geology of Southwestern Idaho and Southeastern Oregon," *U.S. Geol. Survey Bull. 217* (1903), p. 52.

ism. They were erupted on a soil layer containing particles of obsidian, pumice, and dacite, thus furnishing definite evidence that they are younger than the acidic flows which lie upon the older series of basalts. The cinder cone rests upon these two flows, which shows that they reached the surface slightly before its formation. The flows apparently originated somewhere near the base of the cinder cone or immediately to the west of it. The older one occupies a considerable area between the cinder cone and the main Glass Buttes Range. It averages about 10 feet thick, and is characterized by ropy surfaces and very little scoriaceous or vesicular material. Microscopical examination shows the rock to be entirely holocrystalline. It is composed of labradorite, augite, and olivine, with minor amounts of magnetite. The feldspars are wholly or partly included within large individuals of augite, forming a typical ophitic texture. Olivine is abundant in large rounded crystals. The rock is very fresh. The only alteration product consists of a thin rim of brownish-red substance occurring on the border of olivine, which has the color but lacks the cleavage of iddingsite. Very small olivine crystals are entirely replaced by it. The other minerals are perfectly fresh. The crystallinity of this flow is remarkable. Although only 10 feet thick, the flow is holocrystalline almost to its borders.

A flow of porphyritic augite basalt occurs directly above the earlier flow. The two are separated in a few places by a slightly baked soil layer of pumiceous sand of transported origin. The surface of the flow is of pahoehoe type. Pressure cracks from 10 to 50 feet long are much in evidence upon its surface. The flow differs considerably from the earlier one in mineral composition and crystallinity. It is a porphyritic rock containing small phenocrysts of less calcic labradorite than the older flow. These phenocrysts are thickly studded with inclusions of black glass and of acicular to hairlike crystals of a brownish-yellow mineral with a very high refractive index. The groundmass has an intersertal texture and consists mainly of small microlites of sodic labradorite, grains of augite, patches of magnetite, and an interstitial mesostasis of brownish-black glass. Flow structure is pronounced, especially in that portion of the groundmass immediately surrounding the phenocrysts. No alteration products were observed.

Change in composition of the flows.—The difference in composition shown by the petrographic analysis of these two flows points to rapid changes in composition of the original magma, from which the flows were fed, in a very short space of time. Although they are in part separated by a soil layer, this soil is of a transported variety and the original surfaces of the flows show scarcely any alteration from weathering. In the older flow counts made of the proportions of different minerals by comparing areas occupied in thin section show the rock to contain about 65 per cent olivine and augite. In the younger rock the amount of augite present is only about 30 per cent, and olivine is entirely absent. Although considerable amounts of glass are present, it is improbable that the difference in the quantity of the mafics shown in the crystalline portions of the rock is compensated for in the composition of the glass. The labradorite in the younger flow is also of a less calcic variety than that in the older. Changes in viscosity attend the change in composition; although the older flow is of the same thickness as the younger, it must have been markedly more fluid. It is holocrystalline and of ophitic texture, while the younger flow has an intersertal groundmass characterized by large amounts of glass and marked fluxional structure. The crystallinity of the lower flow cannot be explained by assuming that these flows were nearly contemporaneous, and that the upper flow acted as a thermal blanket for the lower, because a thin soil layer is seen to separate them.

THE GLASS BUTTES SERIES

The name Glass Buttes Series is used in this paper to designate a closely related series of rocks of acidic composition that form the main portion of the Glass Buttes Range. This series is repeated by faulting at several places within the range, which gives a false idea of its thickness. Seven lava flows belonging to this series, each of which are at least 50 feet thick, occur on one fault scarp, while two other flows are exposed on the downthrown block of the same fault. This brings the total known thickness of this series up to over 400 feet. It is improbable that the series is much thicker, for the older basaltic flows upon which the acidic types were poured are exposed beneath the younger acidic lavas on several of the fault scarps.

In the field the most striking feature of the lavas of the Glass Buttes Series is the pronounced banding which practically all of the larger flows exhibit. So pronounced is this feature that, when viewed from a slight distance, these rocks look like a vast series of sediments with very well-developed bedding. The banding is remarkably parallel in the lower and middle portions of the flow, but toward the top it generally becomes very much contorted and is finally lost in the thick pumiceous and broken-obsidian caps which cover most of the flows. The surfaces of the lava flows of the Glass Buttes Series must have been entirely covered with loose blocks of obsidian and pumice at the time of extrusion. An eruption of this type has been described by Washington from Fouque Kameni, on the island of Santorini.[1]

Petrography.—The well-banded portions of the lavas of the Glass Buttes are generally light brownish red in color and show perfectly aligned phenocrysts of feldspar and bands of flattened vesicules partially filled with rounded aggregates of colorless hyalite. In thin section the feldspars prove to be andesine, which often shows a ragged oscillatory zoning. The addition of more calcic zones to a sodic nucleus must have been preceded by some resorption, because in each case the calcic zones were deposited on an irregular nucleus, while where more sodic material was added to a more calcic nucleus, the border between the two is well defined. Augite and hypersthene occur in all of the banded lavas studied and are characterized in all cases by marked reaction rims consisting of finely divided reddish-brown material with much included magnetite. In several of the rocks hypersthene is represented only by pseudomorphs of magnetite and of the reddish material. Quartz phenocrysts occur in several of the rocks. They appear to have been very unstable, and where present are very badly resorbed and corroded. The resorption has taken place irregularly, so that the phenocrystic remnants are often of peculiar shapes with finger-like extensions and narrow embayments along their sides. No synantetic minerals are present surrounding these resorbed phenocrysts, the glassy base of the rock penetrating into the innermost recesses of the resorption cavities.

[1] Henry S. Washington, "Santorini Eruption of 1925," *Bull. Geol. Soc. Amer.*, Vol. XXXVII (1926), pp. 357–76, especially pp. 373–76.

In three of the rocks that were studied, andesine appeared to be unstable, as well as quartz, hypersthene, and augite, and showed corroded outlines and marked reaction rims (Fig. 1) consisting of a fine mat of colorless cryptocrystalline grains and scaly material showing low polarization colors. The usual explanation for the resorption of an already formed mineral by the magma from which it crystallized is that progressive change in the composition of the magma has proceeded to such an extent that the earlier crystallized mineral is no longer stable in the liquid which surrounds it. Such an explanation leaves something to be desired, however, in the case of a rock in which such diverse minerals as hypersthene, augite, andesine, and quartz are all unstable at the same time. That the equilibrum conditions under which intratelluric phenocrysts form would be greatly altered by extrusion and consequent loss of volatile constituents and relief of pressure is well known, and it has been pointed out that a logical result of these equilibrum changes is the resorption of phenocrysts formed at depth.[1] It has been especially noted that in certain lavas olivine crystals brought from below tend to be very quickly resorbed.[2] "A condition necessary for its existence seems to have been lost upon extrusion."

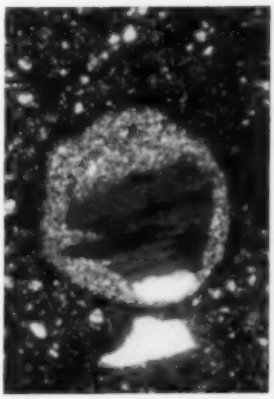

FIG. 1.—Photomicrograph showing a corona around andesine. Glass Buttes, Oregon.

Zonally arranged inclusions of glass are very common in the andesine phenocrysts. They vary from the glassy base of the rock in that they are perfectly colorless and do not contain inclusions within themselves.

The groundmass of the well-banded portion of the flows from the Glass Buttes generally consists of yellowish-brown glass containing innumerable crystallites of various types. Microlites of oligoclase-

[1] Arthur Holmes, *Petrographic Methods and Calculations* (1920), p. 340.

[2] C. F. Fenner, "The Katmai Magmatic Province," *Jour. of Geol.*, Vol. XXXIV (1926), p. 699.

andesine are also numerous, and in some of the lavas become so abundant that they give the groundmass a felted aspect of trachytic nature. Fluxion banding is pronounced. Microlites and crystallites are all aligned parallel to the direction of flowage, and the streams of microlites can be seen to bend around the larger phenocrysts. An exception is seen in one series of trichites, which show no relation to the flow structure and were apparently formed after flowage had ceased. Small, drawn-out vesicles partially filled with aggregates of hyalite are numerous. Quartz is also present in some of these vesicles.

In the upper portion of the flows, in which the banding is much contorted, the groundmass of the rocks takes on a slightly different appearance. The glassy base appears brecciated and shows decided changes in color. Some portions of the glass are nearly opaque, while adjoining areas may be nearly colorless. Aggregates of minute spherulites are very common in these portions of the flows.

Nomenclature.—The naming of these rocks presents several problems. Most of the specimens studied contained phenocrysts of hypersthene, augite, andesine, and quartz set in a glassy base containing many microlites of oligoclase-andesine. Rocks of this nature would obviously be referred to the dacites and would be called hypersthene-augite dacites. In some of the flows, however, quartz is very rare, occurring in small badly resorbed crystals, while in a few of the rocks it could not be detected at all. In addition, quartz was not detected in the groundmass of any of the rocks. There is no reason to believe that there is any appreciable change in the composition of the different flows belonging to this series, either from their relations in the field or from their study in thin section. In those rocks in which the quartz phenocrysts did occur they were unstable as is shown by their corroded and embayed outlines. It is significant in this respect that in those rocks whose groundmass is of trachytic nature, the quartz is either totally absent or very rare. The name "dacitoid"[1] was used by Lacroix in describing lavas which correspond in composition to dacite, but which do not contain modal quartz.

[1] M. A. Lacroix, "Dacites et Dacitoides, à propos des laves de la Martinique," *Comptes Rendus, Académie des Sciences*, Vol. CLXVIII (1919), pp. 297–302.

More recently Washington has proposed the name "hyalodacite"[1] for lavas of this type. Both of these names are based on definite evidence as to the composition of the rock obtained from chemical analysis, however, and consequently cannot be applied to the lavas of the Glass Buttes on the basis of the evidence now at hand. Owing to the inability of obtaining analyses, it is necessary to retain the name "andesite" for those rocks in which modal quartz is not present, although it is highly probable that chemical analysis would show them to correspond more closely to dacites. It might be pointed out, as evidence against this viewpoint, that the mafic minerals, hypersthene and augite, are characteristic of andesites, while hornblende and biotite are more commonly found in dacites. Pyroxene dacites are not rare, however, and have been described from several localities in the West.[2]

Obsidian.—Obsidian, although very common as bowlders in the dry stream channels and as loose blocks in the pumiceous sand of the Glass Buttes region, is rarely found in place. One flow of perlite is exposed at the southwestern corner of the Glass Buttes Range which contains blocks of black obsidian that are not affected by the perlitic cracks. In the central portion of the range a thick flow of dacite contains obsidian in its upper, pumiceous part.

The obsidian is of two types. One of these has a jet-black color in thick pieces, but is almost perfectly transparent in slices one-fourth inch or less in thickness. The other is a variegated type which contains angular black fragments in a brilliant brownish-red opaque base. Some of the variegated types show alternating bands of red and black. The obsidian from this locality is being studied in detail by Mr. R. E. Fuller, and the results of this work are to be published shortly. Further description is, therefore, omitted from this article.

THE OLDER BASALTS

The oldest rocks exposed in the Glass Buttes region are a series of augite and olivine basalts. This series is exposed beneath the

[1] Henry S. Washington, "Santorini Eruption of 1925," *Bull. Geol. Soc. Amer.*, Vol. XXXVII (1926), p. 382.

[2] J. P. Iddings, *Igneous Rocks* (1909), Vol. II.

dacites and andesites on several of the fault scarps in the Glass Buttes, and also forms a considerable area in the northwestern portion of the range. No estimate of the thickness of this series can be obtained in the Glass Buttes region.

Petrography.—The flows belonging to this series are remarkably alike in thin section. They consist of the usual ophitic and intergranular aggregates of labradorite, augite, olivine, and magnetite, and do not differ from the usual types of basalt that occur in other localities. They are slightly more altered than the younger basalts, but are very fresh. Some types are very porphyritic, showing thickly studded phenocrysts of labradorite up to an inch in length.

RELATION OF THE VOLCANIC ROCKS AT THE GLASS BUTTES TO THE SOUTHERN OREGON VOLCANIC FIELD

Lavas of basic and acidic composition are widespread throughout southern Oregon. The acidic and basaltic flows appear to be everywhere conformable, and at several localities are interbedded.[1] Basaltic flows of very recent origin are also widespread. The older basalts and acidic lavas have been referred to the Miocene,[2] while the younger basalts are known to be very recent. In the Glass Buttes region the older basalts and the dacites and andesites probably correspond in age to the basaltic and acidic rocks exposed on Steens Mountain and at other localities in south-central Oregon.

ACKNOWLEDGMENTS

The study of the Glass Buttes lavas was undertaken by the writer while he was in the service of Mr. R. E. Fuller, to whom thanks are due for granting the time spent in the investigation and also for assisting in the field work. The writer also wishes to thank Professor G. E. Goodspeed and Mr. Fuller for assistance and suggestions while engaged in the petrographic study of the material collected.

[1] Per. cit., Mr. R. E. Fuller.

[2] Gerald A. Waring, "Geology and Water Resources of the Harney Basin Region, Oregon," *U.S. Geol. Survey Water-Supply Paper 231*, 1909.

THE SPOKANE FLOOD: A DISCUSSION[1]

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During the summers of 1921 and 1922 the writer, in connection with the routine task of topographic mapping in the Corfu, Scooteney Lake, and Hanford quadrangles, Washington, was able to observe in a reconnaissance way a number of the unusual features that have since been so ably described by Professor Bretz.[2] Although the whole region possesses a fascination that tempts a discussion of many of the problems presented, the writer wishes to confine his attention to one particular phase with which he is most familiar, namely, those records of the glacial history that have been left upon the surface of the Ringold formation in the area south of the Saddle Mountains. An interpretation of these records differing radically from that given by Bretz[3] is believed to fit the field facts more satisfactorily than does his hypothesis, and it has a further advantage in that no catastrophic element is involved in its development.

The Columbia River, after cutting from north to south through the Saddle Mountain uplift below Beverly, swings first eastward, then northeastward, to Wahluke, below which town it swings back sharply again to the general southeasterly course that it follows as far as the junction with the Snake. The Ringold formation, lacustral in origin[4] and of preglacial Pleistocene (?) age, appears as the only

[1] Published by permission of the director of the United States Geological Survey.

[2] J Harlen Bretz, "Glacial Drainage of the Columbia Plateau," *Bull. Geol. Soc. Amer.*, Vol. XXXIV (1923), p. 573; "The Channeled Scablands of the Columbia Plateau," *Jour. Geol.*, Vol. XXXI (1923), p. 617; "The Dalles Type of River Channel," *Jour. Geol.*, Vol. XXXII (1924), p. 139; "The Age of the Spokane Glaciation," *Amer. Jour. Science*, Vol. VIII (1924), p. 336; "The Spokane Flood beyond the Channeled Scablands," *Jour. Geol.*, Vol. XXXIII (1925), pp. 97–115, 236–59.

[3] *Op. cit.*, *Jour. Geol.*, Vol. XXXIII (1923), p. 646; *op. cit.*, *Jour. Geol.*, Vol. XXXIII (1925), p. 115.

[4] George Otis Smith, "Geology and Physiography of Central Washington," *U.S. Geol. Survey Prof. Paper 19* (1903), p. 18; Frank C. Calkins, "Geology and Water Resources of a Portion of East-Central Washington," *U.S. Geol. Survey Water-Supply*

formation on the north and east sides of the river over most of this course.[1] Between the Saddle Mountain water gap and Wahluke it is expressed topographically in the form of a subdued high-level terrace whose summit rim lies at a variable distance back from the river,[2] but below Wahluke the river has so crowded against its east bank as to produce a precipitous, and in many ways spectacular, bluff in the Ringold formation known as the White Bluffs of the Columbia, in allusion to the light gray, white, and cream color of the mudstones and silts that make up the greater part of the formation. The rim of the White Bluffs stands from 300 to 600 feet above the Columbia River between Wahluke and Ringold, the lower levels at the north being correlated with the nearness of the Saddle Mountains and the resultant concentration of the run-off. As will be brought out later, most of this erosion at the north was accomplished under former climatic conditions of less aridity than those prevailing at the present time.

The surface of the Ringold formation above and for several miles to the east of the White Bluffs is essentially a level plain of aggradation.[3] That this plain formerly extended westward 15–20 miles to the Yakima and Rattlesnake ranges is evident from the inadequacy of any alternative possibility even if there were no collateral lines of evidence; the Ringold beds have been undisturbed in the region south of the Saddle Mountains,[4] and the Yakima and Rattlesnake ranges are the only possible limits of the basin in which the lake beds could have accumulated to the present exposed thickness in the White Bluffs. Confirmatory evidence of this westward extension was

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Paper 118 (1905), p. 36. Merriam and Buwalda, however, on the evidence of mammalian remains found at two localities between Hanford and Ringold, conclude that at least part of the series is of flood-plain origin.

[1] John C. Merriam and John P. Buwalda, "The Age of Strata Referred to the Ellensburg Formation in the White Bluffs of the Columbia River," *University of California Publications in Geol.*, Vol. X (1917), p. 255.

[2] All the features here discussed are shown on the Scooteney Lake, Hanford, and Coyote Rapids quadrangles.

[3] Merriam and Buwalda, *op. cit.*, p. 262.

[4] The component of dip measured parallel to the bluff by the writer accounted for a difference in the elevation of a given horizon of only 8 feet in 5 miles, and it is believed that the amount would be of the same order of magnitude if taken in any other direction.

found by Merriam and Buwalda, who state that isolated patches of the Ringold formation appear at various points on the west side of the river.[1]

These Pleistocene (?) lake beds have been removed from the region west of the Columbia by a process of lateral planation by the river.[2] Normal erosion by rainwater is ruled out when the almost complete lack of any dissection by local drainage of the Ringold plain east of the White Bluffs is considered. Further and conclusive proof that the Columbia has shifted over this region is shown by the presence over extensive areas west of the river of coarse stream gravels and cobbles that are similar in size, shape, and lithologic composition to those of the present-day Columbia Channel. Many of these deposits appear as huge river bars inclosing undrained depressions.

The surface of the Ringold plain east of the Columbia is cut by three dry coulees that head at the east end of the Saddle Mountain uplift, in the scabland plexus termed the "Othello channels" by Bretz. After pursuing a southwestward course, these coulees debouch at different elevations as hanging valleys along the White Bluffs. All are markedly U-shaped in cross-section. The master-channel of the three is Koontz coulee, which debouches at Ringold at an elevation of 150 feet above the river. In its lower and better defined portion it is $1\frac{1}{2}$ miles wide and its bed lies from 300 to 350 feet below the flat, undissected Ringold plain which borders it abruptly on the northwest. A subsidiary channel of smaller dimensions (three-quarters of a mile wide, 100 feet deep), which is here treated for convenience as a part of Koontz coulee, leaves the latter about 10 miles back from its mouth, and after following a subparallel course 2 miles southeast of the main channel, enters it again at the point where it joins the Columbia. At its mouth this "parasitic" coulee hangs about 125 feet above the floor of Koontz coulee, but at its source it merges with the main channel in such a way that the cross-sectional profile, instead of presenting a marked topographic break at the junction of the two channels, shows an even ascent from the deepest part, along the foot of the northwest wall of Koontz coulee, to the east wall of the smaller channel.

[1] Merriam and Buwalda, *op. cit.*, p. 262. [2] *Ibid.*

Headward, Koontz coulee opens out, funnel-like, onto a scabland floor, and finally loses its identity in an intricate maze of interlacing scabland coulees, the Othello channels of Bretz. These channels cross the divide at the east end of the Saddle Mountains over a front of several miles. Huge rock-bound depressions are characteristic land forms throughout this tract, the most striking example being the one that holds Scooteney Lake. Neglecting the linear tract about 5 miles long that is inclosed within the top depression contour northwest of the lake, the rimrock basin proper is a little over 2 miles long, 1,000 feet wide, and 150 feet deep.

The two other remaining dry coulees are of mutually comparable size, averaging less than half a mile in width and from 75 to 150 feet in depth, and are thus much smaller than Koontz coulee. They head at essentially the same point in the west rim of Koontz coulee 12 miles above its mouth, at an elevation of 250 feet above its bed, and, after following divergent courses, reach the bluff of the Columbia at points 2 and 15 miles, respectively, above the mouth of Koontz coulee and at elevations of 425 and 300 feet, respectively, above the Columbia. Both in turn show remnants of still shallower braided channels at higher levels, appearing as short shunts off the primary channels. The southern of these dry coulees maintains its U-shape practically up to the point where its profile breaks off abruptly to the level of the Columbia; the inclosing walls of the northern coulee, on the contrary, begin to recede diagonally and to flatten at a point 5 miles back from the river, so that the incised character of the coulee is soon lost, though the old drainage line can still be traced through to the bluff overlooking the town of White Bluffs.

That all three of the dry channels described previously were produced under drainage conditions widely different from those prevailing at the present time is amply proved by the sage-covered depressions in the two smaller coulees, and by the scattered rock depressions in the upper regions of Koontz coulee.

Mr. Bretz has interpreted these dry coulees as the product of huge glacial torrents that emptied into the Columbia when its flood waters stood at or slightly above the levels of the present mouths of the coulees. That these are at different levels is believed by him to be due to the different stages in which they were abandoned during

the lowering of the flood of the Columbia, Koontz coulee being the last one abandoned. The bed of the river at the time of this flood is believed by him to have been at essentially its present level.

The writer believes that the three dry coulees were formed by the glacially diverted Columbia[1] at a time when the normal river channel lay several miles west of its present channel, and that they have since been converted into hanging valleys by the lateral shift of the river to the east against the soft sediments of the White Bluffs. The higher coulees are believed to be distributaries formed early in the history of glacial drainage across the Ringold plain and abandoned after Koontz coulee had gained the mastery.

That this lateral shift is a reality today is proved by the vigorous manner in which the river is undercutting the bluff. Elsewhere in the region the soft Ringold sediments tend to weather into soil-covered slopes with the obliteration of all natural exposures, even under the existing conditions of aridity; in the bluffs, however, so incessant has been the crowding by the river that the slopes have been steepened far beyond the normal profile of equilibrium, and good exposures have been correspondingly favored to the point where they have become the rule rather than the exception. Landslides off the face of the bluff are numerous, and some of them are uncommonly large. One opposite Hanford has left an undrained depression behind it $1\frac{1}{2}$ miles long, 1,000 feet wide, and 100 feet deep.

Projection of the profile of Koontz coulee to meet the topographic slope on the west side of the Columbia indicates that the river lay approximately 3 miles west of its present position when the coulee

[1] The suggestion that the Columbia River was diverted across the Big Bend country by an ice dam west of the head of Grand coulee is not a new one, but has appeared frequently in the previous literature on the region.

See T. W. Symons, "Report of an Examination of the Upper Columbia River," *Forty-Seventh Congress, 1st Session, Sen. Doc. No. 186*, 1882; I. C. Russell, "Geologic Reconnaissance in Central Washington," *U.S. Geol. Survey Bull. 108* (1893), p. 91; W. L. Dawson, "Glacial Phenomena in Okanogan County, Washington," *Amer. Geol.*, Vol. XXII (1898), p. 203; R. D. Salisbury, "Glacial Work in the Western Mountains in 1901," *Jour. Geol.*, Vol. IX (1901), pp. 721–24; F. C. Calkins, "Geology and Water Resources of a Portion of East-Central Washington," *U.S. Geol. Survey Water-Supply Paper 118* (1905), pp. 43, 44; Karl Oestreich, *Die Grand Coulee* (memorial volume of the Transcontinental Excursion of 1912), American Geographical Society, 1915; A. T. Schwennessen and O. E. Meinzer, "Ground Water in Quincy Valley, Washington," *U.S. Geol. Survey Water-Supply Paper 425* (1918), p. 135.

was formed. The restored profile of the next coulee to the north cuts the west slope of the valley in approximately the same latitude as does Koontz coulee, but 3 or 4 miles farther west. It would hardly be sound to assume that this distance measures the amount of shift made by the Columbia during the time that glacial drainage crossed the Othello Channel divide, since the profile of the higher coulee is not a smooth curve and we have no assurance that it represents the grade of equilibrium. Indeed, the fact that the profile steepens downstream is rather suggestive that it was still unstable at the time that it was abandoned. A graphic solution of the river's position at the time that these channels were cut is further handicapped by the existence of widespread deposits of dune sand, showing considerable relief (75–100 feet), that borders the west side of the river in a belt several miles wide, directly in line with these hanging coulees. No great reliance can therefore be placed on the actual quantitative values given, yet they do express the general order of magnitude.

The process of lateral planation called upon to account for the removal of all of the Ringold beds west of the river was not continuous, but had at least one important interruption. Gable Mountain, a steep east-west trending basalt ridge 6 miles in length, rises abruptly from the gravel-covered lowland west of Hanford to a maximum elevation of 1,116 feet, which is about 175 feet above the level of the White Bluff's rim. Since this barrier was not removed by the river, the amount of shift to the east and north that has occurred to date must have taken place in two stages; the first terminated when the south face of Gable Mountain was reached, the second began when the local drainage had cut a low enough gap around the north side of the rock to divert the river, and is unterminated at the present day. Under the climatic conditions existing today, headward erosion of any local gulch in the face of the bluff would be a very indefinite and slow process, but when we consider that the feat was probably accomplished in glacial or preglacial time, in at least one of which we have evidence for believing that the climate was somewhat more humid, this difficulty breaks down. Gable Mountain presents a problem that has to be explained, whether the interpretation placed by Bretz upon the physiographic history of the White Bluffs region, or the alternative one presented by the writer, is accepted.

It is believed that Bretz's interpretation of the relation of the hanging coulees to the White Bluffs is inadequate to explain (1) the fact that the two smaller dry coulees previously described, although heading at the same place, reach the White Bluffs above the Columbia at different elevations; (2) the fact that a V-shaped valley along the southern base of the Saddle Mountains, which heads in the Ringold plain and was produced entirely by drainage from the southern slope of the mountains, also forms a hanging valley 275 feet above the Columbia, although in this case, as with the northernmost glacial coulee, the south slope of the valley breaks back several miles from the river, so that the lower course of the old drainage across the resulting flat is almost obliterated. No run-off ever flows through to the Columbia today, and the lower valley has been largely choked by sand dunes. The fact that this valley is so completely out of adjustment with the present Columbia is proof to the writer that it was formed under climatic conditions of greater humidity than those prevailing today, and has been converted into a hanging valley by the invasion of the river from the west, with the contemporaneous removal by lateral planation of several miles of the lower course of the valley as originally formed. To interpret the level at which this normal erosion valley and the northernmost glacial drainage valley lose their definition by the retreat of their contiguous walls as the ephemeral base level of the Spokane flood, as Bretz has done, is incompatible with the long period that must have been required for the normal valley to have been eroded.

Mr. Bretz interprets the coarse stream gravels and cobbles that cover extensive areas west of the river as the débris of the Spokane flood. The writer believes them to be normal channel deposits of the Columbia during its eastward shift over the area in preglacial, glacial, and post-glacial times.

In summary, four distinct and independent lines of evidence, in the writer's opinion, point to the conclusion that lateral planation by the Columbia has been the dominant factor in the physiographic development of the White Bluffs region: (1) the relation of the present area of the Ringold formation to its former extent, (2) the hanging character of the normal valley at the north end of the White Bluffs, (3) the landslide topography of the present White Bluffs, and

(4) the widespread gravel deposits on the west side of the river. If the development of the V-shaped valley along the base of the Saddle Mountains can be correlated with the glacial epoch, then we have definite proof that much of this lateral planation is of post-glacial age. This established, the many anomalous features presented by the U-shaped channels become readily explainable in terms of the known physiographic history of the region. Even though the glacial age of the normal valley at the north is denied, the writer believes that the explanation of these hanging glacial coulees as developed in this paper is still borne out by the weight of the analogy between the U-shaped valleys and the V-shaped valley; the latter certainly owes its hanging character to the removal by lateral planation of its lower course.

We are thus under no necessity for believing that any unprecedented flood has produced these abandoned channels; Koontz coulee and its congeners were cut in the easily eroded silts of the Ringold formation by glacial or glacially diverted drainage of not extraordinary amounts.

THE SPOKANE FLOOD: A REPLY

J HARLEN BRETZ
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I have several criticisms of Mr. McKnight's argument in the preceding paper. The first deals with a field interpretation and the others with factors and combinations which I believe he has overlooked or misinterpreted, and with a serious inconsistency in his conception. I also have some field evidence to contribute.

The "hanging" normal V-shaped valley in the northern part of the Hanford Quadrangle is eroded in a subdued scarp, 100–150 feet high and a quarter of a mile to a mile wide. This scarp is a definite thing for nearly 15 miles along its irregularities from White Bluffs northeastward to the foot of Saddle Mountain. Both above it and below are distinctly flatter tracts. The valley in question is but one of several which have been developed on this steeper slope. They terminate on the lower flat because of decreased gradient. Where an extension of this valley would have to enter the Columbia, the White Bluffs of the Ringold formation are 225 feet high and their summit level is at least 600 feet A.T. The flat at the top of the bluffs rises 150 feet in about five miles back to the mouth of the valley (or foot of the scarp), and 50 feet of this is within less than a quarter of a mile of the brink of the bluffs. The gradient of the lower part of the valley itself is 60–70 feet per mile, the average of the entire valley is 100 feet per mile.

It is therefore impossible that the valley once extended farther west and has since become obliterated across the lower flat. It belongs to a class which is common enough in youthful drainage systems where regional slopes to be crossed possess marked convexities. These valleys begin as gullies on the crest of the convexity and lengthen both ways, though the mouths are not extended across the flatter tracts beyond the foot of the steeper slope. There are many similar valleys in the region, particularly on Frenchman Hills, north of Saddle Mountain. They are clearly much older than the glacial

spillways. Indeed, the locations of Koontz Coulee and its neighbors probably have been determined in part by just such valleys. Such normal valleys indicate only one thing about the level of the preglacial Columbia: it was somewhere below their mouths when they were formed. They are not properly described as "hanging." No lateral planation or master valley deepening has functioned in their production. The Columbia might well have been a hundred miles away. And that they have any bearing on the level of the glacial Columbia is absurd. My critic is in error when he imputes this inference to me.

Mr. McKnight accepts my interpretation of the gravel deposits about Gable Mountain as great bars and associated depressions; channel forms. He ascribes them to the preglacial, glacial, and postglacial work of the Columbia and gives them no further consideration. But they cannot be dismissed from the problem so simply. We are making a detailed study, confessedly in the hope of securing a more nearly correct interpretation. To neglect any relevant details will imperil the success of the inquiry.

The magnitude of these gravel bars and channels is such that the post-glacial Columbia cannot be held responsible for any of them south and southwest of the great rounded bar north of Gable Mountain. The west end of the mountain is a great cleaver pointing up the Columbia Valley, bare rock to the summit except for talus accumulations. Just west of the cleaver is a large depression, as low as the river 4 miles distant, though separated from it by nearly 3 miles of gravel 100 feet higher. The depression extends eastward along both sides of the rocky ridge, constituting two large channels, one of them twice as wide as the present Columbia. The floor of both channels *rises* downstream 50–75 feet in the 6-mile length of the ridge. Traced upstream, away from the cleaver of Gable Mountain, the floor of the depression rises 100 feet in a mile and a half. And the immediately surrounding hills, the gravel bars, stand 150 to 200 feet above the depression. Clearly Gable Mountain was an island when these features were formed, and clearly the water surface was more than 600 feet A.T. when the hole into which the cleaver projects, as deep as present river level, was formed by a great deflection eddy. Only the glacial Columbia can be held responsible for these features. The broad flattish tracts and steeper slopes in the gravel look somewhat

like terraces on first inspection. But they cannot be so interpreted, as Mr. McKnight recognizes.

If, now, we attempt to put the immediately post-glacial Columbia anywhere among these channels and bars, it would logically go in the larger, deeper channel along the south side of the mountain. This location is not far from what the projection of the profiles of Koontz and its "parasitic" coulee require. Then, in later post-glacial time, we must shift the Columbia in some way from this channel to the present course, which is essentially no deeper, and in this shift we must pass Gable Mountain and the two glacial river bars which stand between the old channel and the present. One of these bars is at least 2 miles wide, 5 miles long, and 150 feet above the deep place noted. The other is a mile wide, about 4 miles long, and 100 feet above the deep place. Furthermore, a gravel fill then must be made in the head of the abandoned channel, 3 miles long and 100 feet above the deep place. No lateral shifting down a slip-off slope is permissible for this change; it must be an abrupt transfer. I believe that a study of the Coyote Rapids and Hanford sheets will make it obvious that this has never occurred, and it follows therefore that the post-glacial Columbia has always been at least three miles and a half north of Gable Mountain and as far east of this eminence as the longitude of Hanford. Yet the abandoned glacial river channel south of the mountain is as low as the present river surface to the north. The post-glacial Columbia therefore found its broad valley here essentially as deep as at present.

Another puzzle concerning these huge channel forms deals with their successful abandonment without noteworthy modification during the closing stages of occupation. Abrupt diversion might succeed; indeed, it apparently did in the scabland bars and basins back on the plateau. But neither Mr. McKnight nor I can apply this method here. He would have it done by the very gradual process of lateral shifting and valley deepening; I, by an abrupt decrease in volume. Perhaps neither of us is right. I wish to note, however, that rivers do not leave channel forms in their deposits as they shift by lateral planation down slip-off slopes. Deposition on the inside of curves obliterates these. Only terraces or continuous slopes are left. Since the area about Gable Mountain, bearing the great bars and

channels, cannot be interpreted as a slip-off slope, we must conclude that the Columbia has not been west or south of Gable Mountain in post-glacial time. Furthermore, the isolation of the eminence occurred in glacial or preglacial time.

Deposits in the broad valley west of the hanging mouth of the first coulee north of Koontz yield more data that must not be neglected. There is a gravel bar two miles south of Hanford and a mile and a half west of the Columbia, 500 feet A.T. and nearly 150 feet above the river. Sand dunes do not obscure it. About two-thirds of the pebble material is basalt, and its large cobbles and small bowlders are almost all basalt and are very little worn. This bar is traceable northwestward about 4 miles to Gable Mountain. It lies between the two channels which flank the mountain and was built when the mountain was an island in a stream far larger than the present. The glacial Columbia was deep enough and vigorous enough on both sides of Gable Mountain to maintain these channels and to build the subaqueous bar in the protected lee at least 100 feet higher than the lowest channel floor. And by the same evidence, the post-glacial Columbia has been confined to the east side of the bar.

Let us now consider the relationship of this bar to the hanging coulee which mouths four miles and a half east of the bar. It hangs 425 feet above the Columbia, 800 feet A.T. If we add 2 miles to its lower length, i.e., restore 2 miles of the retreating White Bluffs, we narrow the Columbia Channel between the bluffs and the bar as much as anyone would care to do and still allow this major strand of the glacial stream enough volume to shape the east side of the bar. This will put the eastern margin of the glacial river about half a mile west of the present east bank, and not more than 100 feet higher. Some sand dunes have been allowed for in this place. There the projected profile of the hanging coulee will be 725 feet A.T., 275 feet in the air. Mr. McKnight would perhaps increase this projected gradient somewhat, for he remarks that the existing portion steepens downstream, suggesting that it was still unstable when abandoned. But the 500-foot top of the glacial river bar immediately west had an adequate depth of water over it at the time. Its existence debars any placing of the immediately post-glacial Columbia's eastern margin 6 or 7 miles west of White Bluffs (or a distance of that "general

order of magnitude"), as McKnight attempts to do. This situation severely limits the amount of post-glacial retreat of White Bluffs and the post-glacial deepening of Columbia Valley here, by which Mr. McKnight would explain the hanging coulee, and it suggests that my original interpretation may still have some value.

My critic and I both speak of the glacial Columbia as though the term covered a single episode. We both know better. In one of my papers I have described the bars and channels about Gable Mountain as Spokane in age. An alternative conception is that the Gable Mountain bars and channels are Wisconsin in age and that the lateral shift to produce the hanging mouths occurred during the interval between the Spokane and Wisconsin epochs. This would escape the difficulty encountered in the space relations of bar and hanging mouth above noted. But the field data by which the alternative would be supported have not yet been collected. Nor could I prove at present that the Gable Mountain features are clearly all pre-Wisconsin. Though one is tempted to speculate, only more field study can safely indicate what the final interpretation will be.

I wish to call attention to a feature of the White Bluffs which seems significant in this discussion. It is a stretch directly east of the two towns of White Bluffs, where the Columbia swings away from the cliff for about 2 miles. Immediately upstream and downstream the river is now undercutting, and the profile of the bluffs, neglecting landslides, is hardly less than 45° anywhere. The average is nearer 60°.[1] But in the stretch referred to, the slopes are about 25°. They are comparable to the average slopes of the Koontz Coulee bluffs, which are in the same formation (Ringold) and which have had no river at their base since the glacial streams ceased to flow. Several miles of the Koontz bluffs are considerably steeper. I am inclined to think that the post-glacial Columbia has never undercut this stretch. The gentle slope is difficult to explain by Mr. McKnight's conception.

The criticisms thus far set forth are summarized in the following paragraphs.

1. The mouthing of the normal V-shaped valley is determined by the foot of the original steep slope in which it is eroded. Its existence, therefore, has no significance in the problem.

[1] Data taken from the Hanford sheet. I have no field measurements for them.

2. The channels and bars about Gable Mountain are far too large to be ascribed to the work of the Columbia in post-glacial time.

3. If the Columbia had been left in any of these channels on subsidence of the glacial flood, it never could have shifted laterally to its present location without destroying large bars, 100–150 feet above the channel floor.

4. Rivers do not leave channel-bottom débris forms behind them as they widen and deepen their valleys under the conditions imposed by Mr. McKnight.

5. The location of one large bar is so close to the Columbia and to White Bluffs that not more than 2 miles of retreat by post-glacial undercutting can possibly have occurred.

6. The profile of the hanging coulee, directly across the river from this bar, when projected 2 miles into Columbia Valley, is 275 feet above the topographic slope where there must have been a glacial river channel.

7. A portion of White Bluffs where the Columbia now swings away from the cliff has slopes no steeper than those which bound Koontz Coulee. Since it is eroded in the same formation by the undercutting of a large river, it should be of approximately the same age, i.e., glacial.

My final criticism deals with a grave inconsistency in Mr. McKnight's proposed explanation. He would have the surface of the glacial Columbia near the *débouchure* of Koontz Coulee 450–500 feet A.T., or 100–150 feet higher than the present river level. He would have this determined by altitude of its floor. It follows, therefore, that the gradient of the surface of the glacial Columbia was determined by its floor.

Let us investigate this item of gradients. The Columbia today descends 125 feet from the mouth of Wenatchee River to the head of Priest Rapids, a distance of 63 miles; it descends 68 feet in the 10-mile length of these rapids; and it descends 57 feet from the foot of the rapids to the mouth of Koontz Coulee, a distance by river of 42 miles. The ledges which cause Priest Rapids, and several lesser rapids in this 115 miles, have been discovered during the assumed post-glacial deepening. Were there no rapids, the present gradient would be less than 2 feet to the mile.

What was the gradient of the glacial Columbia's surface for 100

miles or so above Koontz Coulee *débouchure?* Could it logically have been much steeper than the present? There were no glacial river rapids over rock ledges in this stretch, for the ledges now being attacked have been incised very little. It seems very improbable that there was a surface gradient of the glacial Columbia, determined by altitude of the channel floor, any steeper than the present.

Now, another glacial river is concerned in the problem: another Columbia. It is the diverted portion that crossed the plateau along the Grand Coulee—Crab Creek route and that split at the eastern end of Saddle Mountain. Part of it crossed this anticlinal feature by way of the canyoned Othello Channels and supplied Koontz Coulee and its neighbors. Part flowed west along the north flank of Saddle Mountain to enter the main Columbia Valley at Beverly. The floor of this latter route does not hang above the Columbia at its *débouchure*, largely because it is a synclinal tract. Its ascent for the first 26 miles east of Beverly is 100 feet. But in the next 6 miles eastward, the floor rises 200 feet. We need trace it no farther, for here was the place of distributary discharge southward to Othello Channels. And the lowest altitude in the head of the diverging spillway is 900 feet, 100 feet above the immediately adjacent Crab Creek Valley, where there then were west-flowing rapids, descending 200 feet in 6 miles.

Can we raise the surface of this diverted Columbia in lower Crab Creek Valley any more above the rock bottom than is allowed at the mouth of Koontz Coulee? McKnight's assumption is that rock floor determines surface of the stream, except for depth of water, and he rules out any extraordinary depth. And the rock floor here has suffered no post-glacial erosion such as is assumed at the mouth of Koontz. The surface of the diverted Columbia, therefore, at this significant place was but little above 800 feet A.T. To discharge toward Othello Channels a sufficient quantity of water to erode the glacial river bed across the divide here and to supply the Koontz Coulee group of spillways the water surface in lower Crab Creek Valley must have been at least 1,000 feet A.T. at this place. This would make it at least 200 feet deep where descending about 30 feet to the mile. And to reach the highest levels scoured by glacial waters here and in Othello Channels, the water surface must have been about 1,150 feet A.T., and the stream 350 feet deep in the

rapids.[1] This is simply impossible by the assumptions on which Mr. McKnight has built. His glacial Columbia never would have discharged through Othello Channels, and he would have had no hanging spillways to explain. Since the discharge did occur, rock floor did not control surface gradients, except in a very general way.

The reader who has followed the argument thus far is now thinking of alternatives and is asking (1) Was not the west-draining lower Crab Creek Valley closed at that time by glacial ice, ice jams, or uneroded Ringold or Ellenburg or Columbia River basalt? (2) Has it not been downwarped subsequent to the Koontz Coulee discharge? (3) Has not Saddle Mountain been upwarped, carrying the Othello Channels relatively higher than when they functioned? (4) Did not Wisconsin discharge, subsequent to the Spokane episode, deepen Lower Crab Creek Valley enough to produce this discrepancy?

My present answer to each of these is "No." Query 4 suggests the most nearly workable alternative. But I believe that there is satisfactory field evidence for each negative, though I hope I am still open to conviction. Since these points were not raised in the preceding paper, detailed discussion is hardly justified here.

I think I am as eager as anyone to find an explanation for the channeled scabland of the Columbia Plateau which will fit all the facts and will satisfy geologists. I have put forth the flood hypothesis only after much hesitation and only when accumulating data seemed to offer no alternative. I would like to see someone not committed to any particular preconception make a field study of that feature of the scablands which Othello Channels typifies; the crossing of divides by the glacial rivers. If the upper scabland levels of Othello Channels, Drumheller Channels, Devils Canyon, Palouse Canyon, and Wallula Gateway can be satisfactorily explained without the ponding at which Mr. McKnight demurs, a long step will be taken toward a more generally acceptable interpretation of the scabland phenomena. Mr. McKnight's analysis neglects this problem entirely.

[1] These measurements are made from this highest part of the diverted Columbia's river bed, which is 5 miles wide. Subsequent erosion has cut a much narrower channel or canyon about 100 feet deeper. Whether this was done later in the Spokane episode or in post-Spokane time does not matter here. When Othello Channels and Koontz Coulee functioned, the water in lower Crab Creek Valley was 1,150 feet A.T.

PEDESTAL ROCKS RESULTING FROM DISINTEGRATION[1]

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ABSTRACT

Pedestal rocks and related erosion features, occurring particularly in desert regions, are generally cited as proof of wind work. In this paper evidence is presented to show that granular disintegration, primarily induced by insolation, may, in some instances, be the chief weathering process effective in the production of such forms.

The discussion of mechanical processes of weathering in most geologic literature stresses the importance of wind work in the formation of the characteristic and usually picturesque erosion features observed in desert regions. The purpose of this paper is to present an example of mechanical weathering wherein pedestal rocks and other erosional forms are derived from granite joint-blocks primarily through the process of granular disintegration and not as a result of eolation.

The locality to be described is Texas Canyon, a shallow canyon-like pass in the south end of the Little Dragoon Mountains in southeastern Arizona. It is part of a larger area of coarse-grained granite which shows the rough bowldery outcrops characteristic of granite in arid regions and varies sufficiently in its erosion to give considerable topographic diversity. A prevalence of widely spaced joints and the advanced erosional state of the joint-blocks produce a rather striking display of large bowlders, domed monoliths, castellated forms, and pedestal rocks of varied size and shape.

Texas Canyon lies at the dry timber-line and, as a consequence, its vegetation is representative of both the desert and the upland zones. The altitude of the canyon floor ranges between 4,500 and 5,000 feet. The climate is semi-arid, with frosts and occasional snow in winter and very hot days and cool nights in summer. Daily as well as seasonal temperature changes are large. The annual precipi-

[1] Presented before the American Association for the Advancement of Science, Southwest Division, Santa Fe, New Mexico, April, 1927.

tation is about 16 inches and occurs in two rainy seasons: winter rains due to general storms, and torrential local showers during the summer months.

The soil mantle, where present, is a coarse gravelly, highly siliceous loam composed chiefly of residual granite débris ranging in size from 2- to 200-mesh and finer. It varies in thickness up to 6 inches and shows a marked tendency to consist of coarser granules on its upper surface, the diameters of which vary between one-quarter and one-half inch. Small halos of iron stain frequently surround the biotite grains, producing a slight discoloration in the otherwise light-gray color of the granite débris. Examination under the microscope reveals the rather surprising fact that even the finest material is essentially made up of the original constituents of the granite, plus a little hydrated iron oxide and some organic matter, and that the feldspar grains are remarkably fresh looking and, therefore, free from kaolinization in any notable amount. This paucity of secondary minerals well illustrates and emphasizes the limited activity of chemical decomposition in surface weathering for this region. Pronounced evidence of weathering being effective downward in the granite underlying the surface is shown only in the close proximity to live-oaks whose root systems have been exposed by road-cuts. In such places, the effects of both mechanical and chemical processes are apparent; the former in the disruption of granite by root growth, and the latter in the partial kaolinization of the feldspars and the decomposition of most of the biotite, as indicated by the brown iron-stained appearance of the crumbly rock.

The areal arrangement of the numerous isolated bowlders and outcrops of granite, which at first glance appears chaotic, is controlled by the jointing of the original igneous mass. Some of the bowlders appear to rest solidly on the soil mantle or on the underlying granite, but more often they are perched singly or in groups upon other bowlders or domed joint-blocks, or high on the rounded tops of larger monoliths. In the majority of cases these isolated perched rocks are of such shape that a larger mass above rests on a smaller base or pedestal, and are therefore called pedestal rocks or, in some instances, balanced bowlders. Typical examples are shown in Figures 1 and 2.

Weathering of the pedestal rocks, bowlders, and joint-blocks should not be expected to show any more, if as much, evidence of

FIG. 1.—A group of perched and pedestal rocks. The foreground clearly shows the coarse gravelly character of the soil mantle.

FIG. 2.—"The Thumbscrew"

chemical decomposition as the granular material of the surface mantle; and they do not, with the exception of concentration in thin

crusts and stains of brown to black hydrated iron oxide or limonite. This limonitic deposition occurs on the underside of a pedestal rock, well down toward the base, or on the bowlder or block below and on that particular part of its surface immediately under the overhang of the upper block. The limonite is evidently the result of chemical decomposition of biotite in the mass above and is deposited in its present position by means of the drip curtain and inner film formed by rain, as explained by Bryan.[1]

Scattered on the upper surfaces of the blocks supporting the perched rocks and on the ground surface surrounding them are many loose grains and granular fragments of fresh granite débris; also large, well-developed crystals of orthoclase up to two and one-half inches in length. The position and appearance of this débris is such as clearly to indicate that it has come from the mass above. Insolation, and other forces, apparently loosened the individual fragments sufficiently so that they fell away by gravity, or else the force of rainwash or wind may have assisted in their removal. The mineral grains in the parent-rock surfaces are often in so loosened a condition they can be readily rubbed off or picked out by hand; this is especially true for the projecting orthoclase crystals, and they may frequently be "picked" from a bowlder as one would pick berries from a bush. Numerous shallow depressions several inches in diameter occur here and there over the surfaces of many of the bowlders; these are probably the work of insolation and rainwash combined. Rainwash also appears to be an effective agent in the widening of joint cracks, some of which are over a foot in width and distinctly show evidence of the action of running water.

Granular disintegration is probably the most effective process in the weathering of extremely coarse-grained granite. Whether this process of disruption results from insolation and heat radiation, or is caused chiefly by frost action or the wedgework of salts is a debatable question; probably all three, in varying degree, are influential. An expansive force induced by the crystallization of secondary minerals of larger volume, along the cleavage cracks of crystals and between mineral grains, may be a factor in disrupting the rock, but the minor amount of such alteration products in evidence here would

[1] Kirk Bryan, "Pedestal Rocks in the Arid Southwest," *U.S. Geol. Survey Bulletin 760* (1925), pp. 3–4.

appear materially to limit its importance. Frost action, during the short, intermittent period in which it is effective in this area, is not believed to be the primary agent in loosening the component mineral grains of the granite, although it could well be more important than is at present realized. Apparently, differential expansion and contraction of the different mineral constituents of the granite as caused by diurnal temperature changes must be the principal factor operative in this particular case. However, Blackwelder's recently published[1] experimental data relative to conditions influencing fire spalling indicate that daily temperature changes alone are quite inadequate to cause rock breakage; further, these results confirm his earlier published[2] opinion, based on field and laboratory evidence, that insolation is not an important factor in rock weathering. But the papers just cited deal mainly with fine-grained rocks and the process of exfoliation, a form of disintegration in which surface scales and slabs are parted from the underlying mass. In the present example of weathering, on the other hand, the rock is a very coarse-grained granite, the individual grains probably averaging over half a centimeter in diameter—locally much more—and the process of exfoliation plays no important part, being observable only in small amount on but few pedestal rocks, and always on the extreme undersides or that portion of the overhang close in to the base. Inasmuch as the relative degree of expansion should be greater the larger the individual mineral grains and likewise the degree of possible cumulated strain resulting from many repetitions of such movement, it does not appear unreasonable to assume that insolation may be of importance in the granular disintegration of coarse-grained granitic rocks, and that it may become of proportionately greater importance as the size of grain increases.

The principal process of weathering involved in the production of these particular erosional forms is clearly mechanical. And that wind scour or corrasion is not effective in their formation is equally clear. There is no evidence of wind-blown material, neither could any movement of sand or dust be detected on a visit to the area on a

[1] Eliot Blackwelder, "Fire as an Agent in Rock Weathering," *Jour. Geol.*, Vol. XXXV (1927), pp. 136–38.

[2] Eliot Blackwelder, "Exfoliation as a Phase of Rock Weathering," *Ibid.*, Vol. XXXIII (1925), pp. 793–806.

day of high wind. The coarse granitic débris on the surface of the soil mantle is too large to be moved by the wind and, together with grass and other small plant roots, holds in place the finer material, while the whole is shielded from much of the wind's direct force by the larger forms of vegetation. Moreover, the pedestal rocks are generally from 10 to 40 feet above the ground surface, and the effective height for wind scour is held to be only some 2 or 3 feet. And, finally, the rock surfaces are nowhere polished from wind abrasion, but, on the contrary, are decidedly rough, owing to the projecting coarse grains of feldspar and quartz. This roughened-surface effect is greatly increased by the frequent occurrence of large orthoclase crystals which may project an inch or more beyond the general surface. This character of surface is commonly considered to be a typical result of mechanical disintegration of granular rocks under daily changes of temperature.

CONCLUSIONS

Aside from the fact that the number and size, odd shapes and positions of the bowlders of erosion previously described produce a rather spectacular type of scenery, they are of interest geologically from the standpoint of weathering processes.

The evidence is believed to indicate clearly that granular disintegration is the principal process of weathering involved, and results mainly from insolation, although frost action and the wedgework of salts are no doubt minor contributing factors.

The widely accepted idea that pedestal rocks occurring in desert regions result chiefly from wind work does not hold in this instance. As pointed out by Bryan,[1] there are undoubtedly many processes by which pedestal rocks are produced, and more than one may be operative in a given case, but even in arid regions they are probably produced primarily by other processes than wind erosion, although there is no inherent reason to prevent their production by this process.

It is therefore concluded that, older opinion to the contrary, the presence of pedestal rocks in desert regions is not necessarily conclusive proof of wind work.

[1] Kirk Bryan, "Pedestal Rocks Formed by Differential Erosion," *U.S. Geol. Survey Bulletin 790A*, 1926.

REVIEWS

The Geology of the Netherlands East Indies. By H. A. BROUWER. "University of Michigan Studies, Scientific Series," Vol. III. New York and London: Macmillan & Co., 1925. 23×15 cm. Pp. xii+160; pls. 18; figs. and maps 17. $2.50.

When R. D. M. Verbeck, at the end of his monumental *Rapport sur les Moluques* (Batavia, 1908), drew up a general survey of the tectonic relationships in the Dutch East Indies, he had to rely mainly on his own field-observations accumulated during some twenty-five years of study in the Malay Archipelago. Since that time quite a number of younger geologists have carried on the work of the great master; and it is quite fitting that one of the most active among them should have been invited by the University of Michigan to give a course of lectures on the geology of that extremely interesting region. These lectures have now been edited by Dr. L. M. Gould and made available, in book form, for a larger public. In five chapters the following topics are dealt with: i, "Major Relief Features and Their Origin"; ii, "Historical Geology"; iii, "Major Tectonic Features"; iv, "Volcanoes and Earthquakes"; v, "Economic Geology."

The book gives a short though comprehensive summary of most of what is known concerning the geology of this important area between the continents of Asia and Australia. Its importance is derived from the fact that here is the meeting-point of two of the greatest zones of crustal weakness on the earth, viz., the Mediterranean and the circumpacific geosynclines. In keeping with this fact, tectonic problems have received special attention, particularly the tectonics of the eastern part of the Malay Archipelago—this area of deep-sea basins and islands in the process of active mountain-building—which has been the author's main field of study. The wealth of pertinent and miscellaneous information within so short a scope is tremendous. While this is undoubtedly commendable, yet the lack of an adequate map makes the text unduly hard reading for one who is not thoroughly familiar with the local geography. But since this book is the only comprehensive and above all authoritative work in English on the geology of that important region, we should be grateful to author, editor, and publishers alike for such as it is. Its reading

is best preceded by a perusal of Verbeck's *Rapport* mentioned above, particularly pages 826–35.

In this connection it may not be amiss to warn against a recent German compilation of similar scope entitled *Die Geologie von Niederländisch-Indien*, by E. Landenberger (Stuttgart: Erwin Nägele, 1922). This book is woefully lacking in understanding and in the exercise of critical judgment, both of which qualities are especially needed for a compilation. M. W. S.

Verbeck Memorial Volume (*Verbeck Gedenkbock*). The Hague: Mouton & Co., 1925. 28×20 cm. Pp. vi+648, with pls., figs., and maps. $3.00.

Often, in Europe, a memorial volume is dedicated to a great leader in science on the occasion of some signal event in his life, to which volume his students, friends, and admirers contribute articles. The volume under notice, which has been published under the auspices of the Geological Society of the Netherlands and Colonies, is such a collection of articles dedicated to Dr. R. D. M. Verbeck upon the completion of his sixtieth birthday. Verbeck, the grand old master of Dutch geologists, has been for more than an ordinary man's life the undisputed leader in geological research in the Dutch East Indies. In keeping with his field of interest, which was the geology of the Western Pacific, contributions have been solicited from prominent geologists in many countries with similar interests. The result is an extremely valuable collection of papers dealing with geological, petrographical, and paleontological problems of the Western Pacific. All together forty-five articles in Dutch, English, French, and German have been contributed by scientists from Australia (1), the federated Malay states (2), France (2), Germany (3), Italy (2), Japan (2), New Zealand (7), the Philippine Islands (1), Switzerland (3), the United States of America (3), besides from Holland and the Dutch East Indies (20). American geologists are represented by Roy Dickerson on "Climate of the Philippines during Tertiary and Quaternary Times"; by W. H. Hobbs on "The Unstable Middle Section of the Island Arcs"; and by Warren D. Smith on "The Geologic Structure of the Philippine Archipelago." It is impossible here to review any one in detail or even to reprint the complete Table of Contents. Suffice it to state the impression that while the volume at present is indispensable to anyone interested in the geological problems of the Western Pacific, it is likely to remain, for a long time to come, a fundamental source of information on those problems.

Royally gotten up, with splendid illustrations, the book is a most worthy tribute to the memory of Dr. R. D. M. Verbeck, who died a few months after the dedicatory ceremony.

M. W. S.

Pflanzen als Gesteinsbildner. By JULIUS PIA. Berlin: Gebrueder Borntraeger, 1926. Pp. 355; figs. 166.

This book treats of the capacity of certain plants to form rocks, and it really is a pioneer in its field, since it brings together into one volume the fruits of investigation of many topics thus far available only in a widely scattered literature. While coal and petroleum have been studied very exhaustively, and the results have been recorded in many a standard volume, some of the other economically important materials, such as free sulphur, sulphur compounds, iron, limestone, etc., which owe their genesis to plant organisms have been treated as detached studies; and only by tiresome search are the results available for general use. Consequently this book is very welcome. Its importance as a collection of findings is not limited to fields of botany or paleobotany, but bacteriology, chemistry, and, above all, economic geology share in the composition of this work. The outline which the author followed is logical from the standpoint of the botanist and paleobotanist; but since the book seems to be a guide for the economic geologist, it is rather illogically arranged to serve its best purpose. However, this minor defect is amply compensated by a splendid description of the plants and their deposits, and by the enlightening diagrams.

After bringing out the fact that plants are far more productive of economically important deposits than are animals, the author begins his description with the lowest of all plants, the bacteria. He studies, in order, those responsible for the deposition of sulphur, the compounds of sulphur, iron, and finally limestone. Of these the first three are rather meagerly treated; additional recent literature would undoubtedly have thrown more light on the activities of these important organisms.

In a further chapter he describes the lower algae, of which some are capable of depositing calcareous sinter, while others are responsible for the precipitation of siliceous sinters. Both deposits are found in the immediate vicinity of hot springs. On the other hand, some of these algae give rise to siliceous deposits in the deep sea; whereas those thriving in shallow waters precipitate limestone. Higher types of algae, such as the green, brown, and red algae, are described as limestone-formers. Even certain

mosses, gymnosperms and angiosperms are endowed with the same capacity. In addition, some particular unicellular plants, by their life-processes, initiate the fermentation of vegetable matter under water. This is the first stage in the formation of carbonaceous material, and hence is of eminent importance.

The closing chapter, which takes up more than half of the entire book, contains an account of the origin of coal and petroleum and a description of plants that give rise to these products. Whereas the former receives a great deal of attention, perhaps more than is necessary, the latter is barely touched on. The author credits plants more than he does animals for the origin of petroleum, but at present this can obviously be only a matter of conjecture. Considering the rapid advance of recent research in the field of petroleum geology, it is to be regretted that the extensive American literature has been entirely ignored.

W. A. W.

Geology of Alabama. By EUGENE A. SMITH, GEORGE IRVING ADAMS, CHARLES BUTTS, LLOYD W. STEPHENSON, AND WYTHE COOK. University of Alabama, 1926. Pp. 312; 1 areal geology map; pls. 97; figs. 3.

This volume is the result of a co-operative study by the Geological Survey of Alabama and the United States Geological Survey, in which all available information has been compiled and modified by data secured on reconnaissance surveys. The text is a detailed description of topography, stratigraphy, structure, economic geology, and geologic history, broadly correlated with the geology of the Appalachian and Coastal Plain provinces. An areal geology map, scale 1:500,000, with columnar and cross sections, accompanies the report.

The chapter on Paleozoic rocks is the longest and most detailed. It contains a correlation table for Alabama and Tennessee, showing the old and revised classifications, as well as a paleogeographic map for each formation. The most significant changes in the classification are the subdivision of the "Pelham" limestone into the Beekmantown and Chazy, and the "Knox Dolomite" into five formations.

Discussion of the Mesozoic and Cenozoic formations is similar to that of the Paleozoic. The distinctive feature of the Mesozoic chapter is a correlation table of the state, showing faunal relationships; and of the Cenozoic chapter, numerous lithologic sections with accompanying faunas.

A type fauna and flora of each formation is illustrated, and there are numerous photographs of the topography and structure cited in the text.

R. W. P.

Geology and Ore Deposits of the Ducktown Mining District, Tennessee. By W. H. Emmons and F. B. Laney, with the active collaboration of Arthur Keith. Professional Paper 139, U.S. Geological Survey.

The rocks of the Ducktown district are metamorphosed Lower Cambrian sediments. They all belong to the Great Smoky formation and consist predominantly of graywacke with some arkose, slate, conglomerate, mica schist, garnet schist, and staurolite schist. There is a definite zone of calcareous sediments, probably just below the staurolite schist. It does not outcrop and its presence was unsuspected until it, or its equivalent marble, was found in the mines. The only igneous rocks are a few small dikes of gabbro and pegmatite.

The rocks of the Great Smoky formation are intensely folded and most of the folds are overturned toward the northwest. The productive portion of the district appears to be part of a closely compressed and much-faulted dome.

The minerals of the ore deposits are typical of contact metamorphic deposits, but no igneous rock capable of accomplishing such metamorphism is known in the district. The ore bodies are broadly tabular or lens shaped. They are parallel to the foliation of the schist. The ore grades along the strike and down the dip into lime silicate rock or into marble. The metallic minerals are pyrrhotite, pyrite, chalcopyrite, and a little sphalerite and galena. Actinolite is the dominant gangue mineral. Where the copper content is over 1.4 per cent the material is considered ore. The gossan has a maximum thickness of 100 feet. Below the gossan there is a chalcocite zone some three or four feet thick.

The conclusion is reached that the ore bodies are replacement deposits in a limestone that had been complexly folded and faulted. The source of the ore solutions is not known. The deposition of the ores was associated with extensive silication and silicification. The mineralizing solutions probably came from a deep-seated granite similar to the granite in the neighboring Ellijay quadrangle. The age of mineralization is not exactly known, but presumably it occurred at or soon after the end of the Paleozoic. Mineralization occurred in two episodes. During the first the limestone was replaced by pyrite and silicates. During the second the later

hypogene sulphides replaced all the minerals of the ore zone as they existed at that time. The schists are mineralized to some extent adjacent to the lodes, but little of this mineralized country rock has been mined as yet.

Reserves are sufficient for many years' requirements. Moreover, the deposits now exploited are from anticlines the crests of which are near or were not far above the present surface. The surface rocks nearly everywhere are of the series that is found above the ores. The ore horizon without much doubt lies under most of the area.

A. B. S.